



## **Rotorua Airshed Modelling Investigation Final Report**

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*Prepared for*  
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## Executive Summary

An assessment has been undertaken to address the requirement for Environment Bay of Plenty to better understand the nature and causes of PM<sub>10</sub> air pollution in the Rotorua region, and in particular provide information to assist the Council to develop policies to ensure compliance with the National Environmental Standards: Air Quality (NES) by 2013.

### Methodology

This assessment has been carried out using:-

- Analysis of the complete historical air quality monitoring record
- The newly developed Environment Bay of Plenty Rotorua Emissions Inventory
- Meteorological data from a number of stations around the North Island
- The model TAPM (The Air Pollution Model) to obtain upper air profiles data.
- Shuttle radar and Terralink for topography data.
- The model Calmet, to obtain meteorological fields for modelling.
- The model Calpuff for modelling contaminant emissions over Rotorua.

The results can be used to:-

- Understand the nature and causes of degraded air quality in the Rotorua airshed – principally for PM<sub>10</sub>.
- Test the efficacy of various emissions reduction strategies.

### Modelling results

The modelling results obtained show:-

- High concentrations of PM<sub>10</sub> occur across much of Rotorua, particularly in the west and southwest parts of the city, and around small sections in the east.
- Peak values can reach over 100  $\mu\text{g m}^{-3}$ , with large areas exceeding the 24-hour standard value of 50  $\mu\text{g m}^{-3}$ .
- The peak number of exceedence days is 23, which is consistent with the monitoring.
- The main source of high PM<sub>10</sub> is from domestic home heating emissions, affecting large parts of the city. Industrial emissions affect a smaller area, within 1-2 kilometres around the eastern industrial site, but do not result in exceedences by themselves. Vehicle emissions do not appear to affect the PM<sub>10</sub> concentrations greatly (except perhaps for a few very localised spots within a few metres of busy roads).
- The current monitoring sites indicate the range of concentrations occurring, with the Edmund Rd. site being located in one of the peak concentration areas, the Pererika St. site in a mid range urban area, and the Fenton St. site in a lower exposure central city area. Monitoring in the south eastern part of the city may produce some slightly higher results than Edmund Rd., but not significantly.
- There are no exceedences of the next highest emitted pollutant – nitrogen dioxide (NO<sub>2</sub>) – with 1-hour peak values less than 10% of the standard. It is unlikely than any other contaminants (e.g. carbon monoxide, sulphur dioxide, ozone and volatile hydrocarbons) will have any significant high concentrations.

The current situation in regard to worst case peak  $PM_{10}$  concentrations due to all sources (domestic heating, transport, industry and natural background), is summarized in Figure S1.



**Figure S1. Worst case daily  $PM_{10}$  concentrations currently occurring in Rotorua. Areas within the red line exceed the standard of  $50 \mu\text{g m}^{-3}$ .**

Figure S1 shows that currently much of urban Rotorua can experience exceedences of the standard, and in the western suburbs in particular this can occur many times during the winter months because of high emissions from domestic wood burning for heating.

#### Reduction scenarios

The modelling has also been used to test the effectiveness of various reduction strategies.

These included measures to reduce domestic home heating emissions (by 40% and by 60%), reductions in transport emissions (by 15%), and reductions in rubbish burning and emissions from school boilers. The only completely effective scenario – resulting in complete compliance with the  $PM_{10}$  standards – was a 60% reduction in domestic home heating emissions across the entire city, shown in Figure S2.

**Figure S2. Modelling result for a 60% reduction in domestic home heating emissions across the city, showing compliance with the standard of  $50 \mu\text{g m}^{-3}$ .**

Other reduction scenarios show lower concentrations, but do not achieve complete compliance. For instance one scenario examined the effect of only applying the 60% reduction in the north western suburbs, shown in Figure S3.



**Figure S3. Modelling result for a 60% reduction in domestic home heating emissions just in the north western suburbs**

Figure S3 shows that lower concentrations are only achieved in those areas that achieve the emissions reductions, and that other parts of the city remain with high concentrations.

#### Summary

Overall, this modelling study has shown that the high concentrations of  $PM_{10}$  currently occurring in Rotorua exceed the National Environmental Standard over much of the city. The only scenario tested that achieves

compliance with the standard is a 60% reduction in domestic home heating emissions across the entire city (along with the expected 15% reductions in transport emissions, and eliminating rubbish burning).



## 1. Standards

The National Environmental Standards for air quality (NES) were introduced by the Ministry for the Environment through national environmental standards regulations in October 2004. These include ambient air quality standards for carbon monoxide (CO), fine particles (PM<sub>10</sub>), nitrogen dioxide (NO<sub>2</sub>), sulphur dioxide (SO<sub>2</sub>) and ozone (O<sub>3</sub>) – see Table 1.1 below. The regulations aim to minimise breaches of national standards air quality standards by 2013. From now until 2013, an annual steady improvement in air quality in polluted areas is required. This steady decrease in pollution levels is to be in the form of a 'straight line path' (SLiP) or a 'curved line path' (CLiP) – the line between current peak levels and levels required by 2013. After 2013, no resource consents will be granted to discharge particulates if the air quality standard is still being breached.

In September 2005 regional councils and unitary authorities identified forty-two airsheds where air quality is likely, or known, to exceed the New Zealand National Environmental Standards for Ambient Air Quality. All but one of the sixty airsheds contain hotspots where PM<sub>10</sub> are an issue at certain times of the year. The other remaining airshed at Marsden Point, Northland also has the potential to exceed the sulphur dioxide standard. Airsheds and their boundaries were drawn by councils using existing knowledge of air quality in the region, the location of significant sources and the effects of topography and climate on the dispersion of pollution (Ministry for the Environment, 2006).

**Table 1.1 National Environmental Standards for Ambient Air Quality**

Contaminant	Standard	Time Average	Allowable exceedences per year
Particles (PM <sub>10</sub> )	50 µg m <sup>-3</sup>	24-hours	1
Sulphur dioxide (SO <sub>2</sub> )	350 µg m <sup>-3</sup>	1-hour	9
	570 µg m <sup>-3</sup>	1-hour	0
Carbon monoxide (CO)	10 mg m <sup>-3</sup>	8-hours	1
Nitrogen dioxide (NO <sub>2</sub> )	200 µg m <sup>-3</sup>	1-hour	9
Ozone (O <sub>3</sub> )	150 µg m <sup>-3</sup>	1-hour	0

Most airsheds are drawn around towns and cities where pollution levels may be higher. Some regions (for example - Waikato and Wellington) have large airsheds that cover a number of pollution sources in areas where the topography is similar, or as in Wellington's case, contained within valleys. Otago Regional Council, on the other hand, has identified 22 settlements where air quality may possibly be an issue. These geographically separated areas have been grouped into four airsheds according to their similarity in topography and climate.

## 2. Airsheds

### Rotorua airshed

For the setting of airsheds, as defined in the context of the National Environmental Standards for Ambient Air Quality, the Bay of Plenty region possessed a small but diverse set of emission scenarios to base its airsheds on. Industrial sources in Kawerau and Whakatane and population growth in Tauranga are typical of many airshed designations. However Rotorua, due to its abundance of geothermal emissions and sheltered nature, has a unique status. Figure 2.1 shows the Rotorua airshed in Bay of Plenty.



**Figure 2.1** The Rotorua airshed within the Bay of Plenty region.

The geothermal field underneath Rotorua has one of New Zealand's last remaining areas of major geyser activity, at Whakarewarewa. Geothermal activity is a major tourist attraction



and of vital economic importance to Rotorua and the region, and tourism earns in excess of \$300 million a year for the Rotorua district.

### 3. Emissions Inventory

#### Rotorua emissions inventory

The full emissions inventory for Rotorua has been completed, under a separate project with Environment Bay of Plenty and Graham Environmental Consulting Ltd. The data have been used as the basic inputs to the airshed modelling process. A full description can be found in the separate inventory report "*Rotorua Air Emissions Inventory. Environment Bay of Plenty Report. 2007/02.*"

### 4. Monitoring Data

#### Monitoring sites

There are three monitoring sites in the Rotorua urban area, located as shown in Figure 4.1

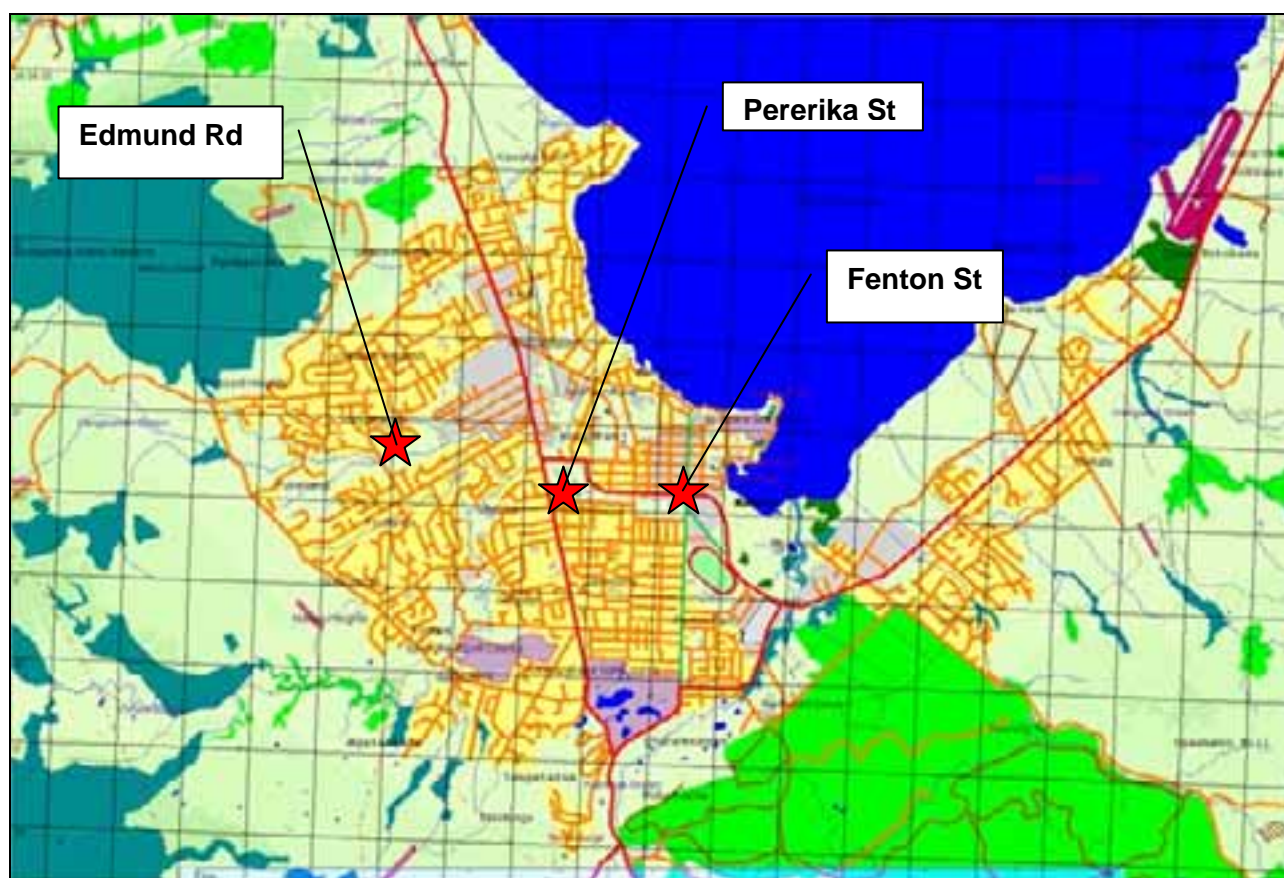


Figure 4.1. Location of the air quality monitoring sites in Rotorua.



## Existing concentrations - PM<sub>10</sub>

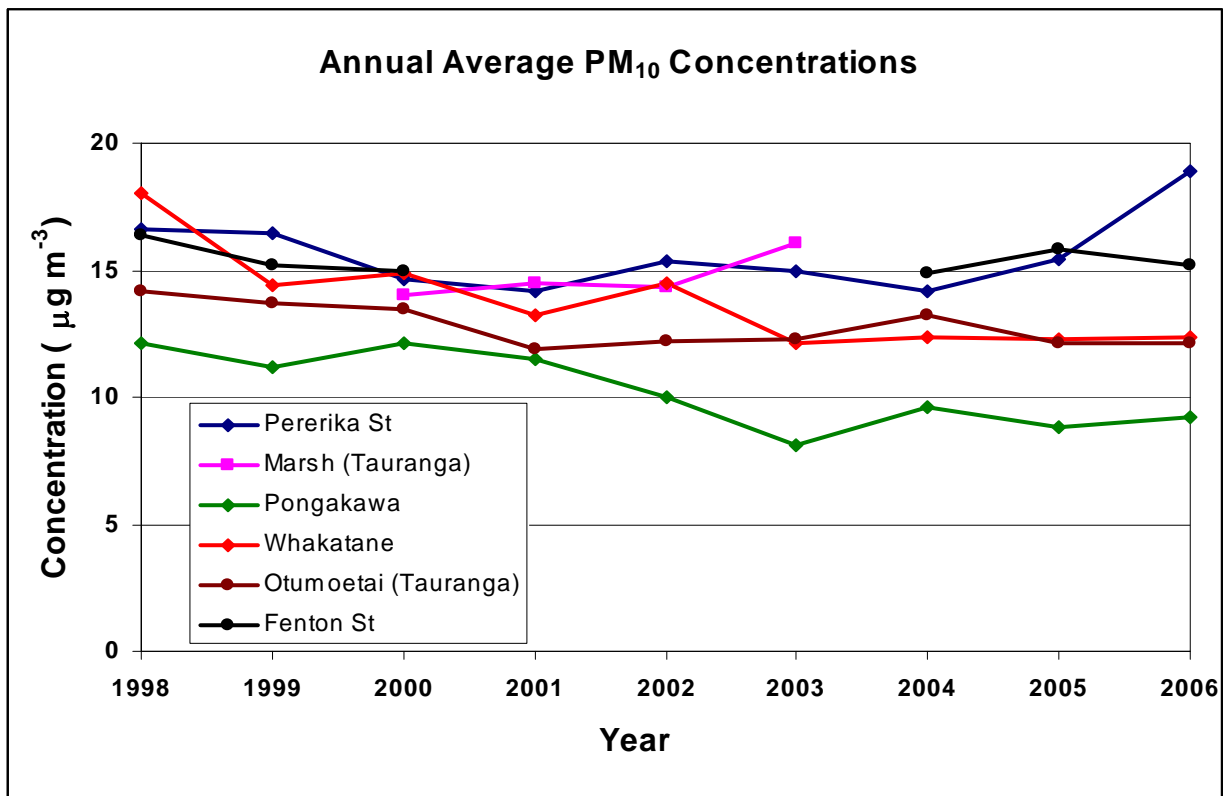
Table 4.1 shows a summary of statistics from the monitoring undertaken throughout the Bay of Plenty region, up to the end of 2006.

**Table 4.1 PM<sub>10</sub> monitoring undertaken in the Bay of Plenty Region.**

Site	Dates of monitoring	Method of monitoring	Number of Exceedences recorded
Rotorua (traffic) Fenton St	Dec 98 to Feb 99 & Dec 04 to present	TEOM	5
Rotorua (residential) Pererika St	98 to present	TEOM	31
Rotorua (residential) Edmund Rd	Mar 06 to present	TEOM	41
Tauranga (traffic) Marsh St	Mar 00 to Feb 01 & Nov 02 to Feb 03	TEOM	2
Tauranga (residential) Otumoetei Rd	97 to 06	TEOM	0
Whakatane (residential)	97 to 06	Partisol	1
Pongakawa (background)	97 to 06	Partisol	0

Table 4.2 and Figure 4.2 show a summary of the long term trends in PM<sub>10</sub> using the annual average, up to the end of 2006.

More recently, starting in early 2006, a new monitoring site has been established at Edmund Rd. This has shown many PM<sub>10</sub> exceedences in the winter of 2006 and 2007.



**Figure 4.2 Trends of the annual PM<sub>10</sub> concentration at several Bay of Plenty sites**

### Data summary

Figures 4.3, 4.4 and 4.5 show the time series for a selection of the daily PM<sub>10</sub> monitoring data at all Rotorua sites for 2005 and 2006.

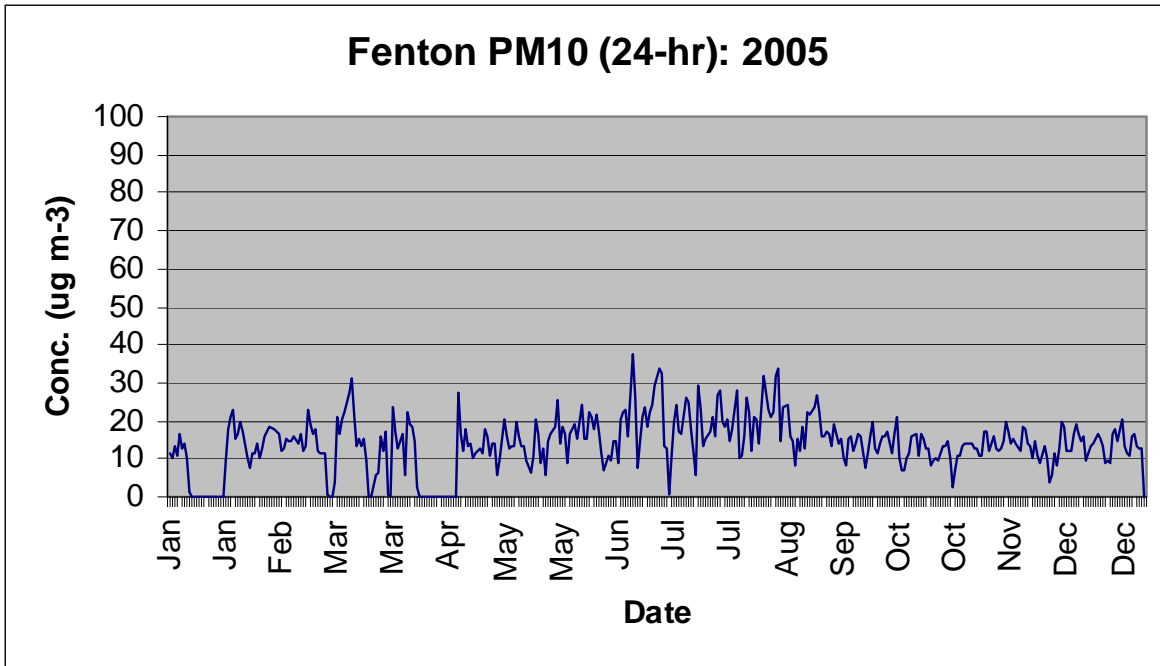


Figure 4.3

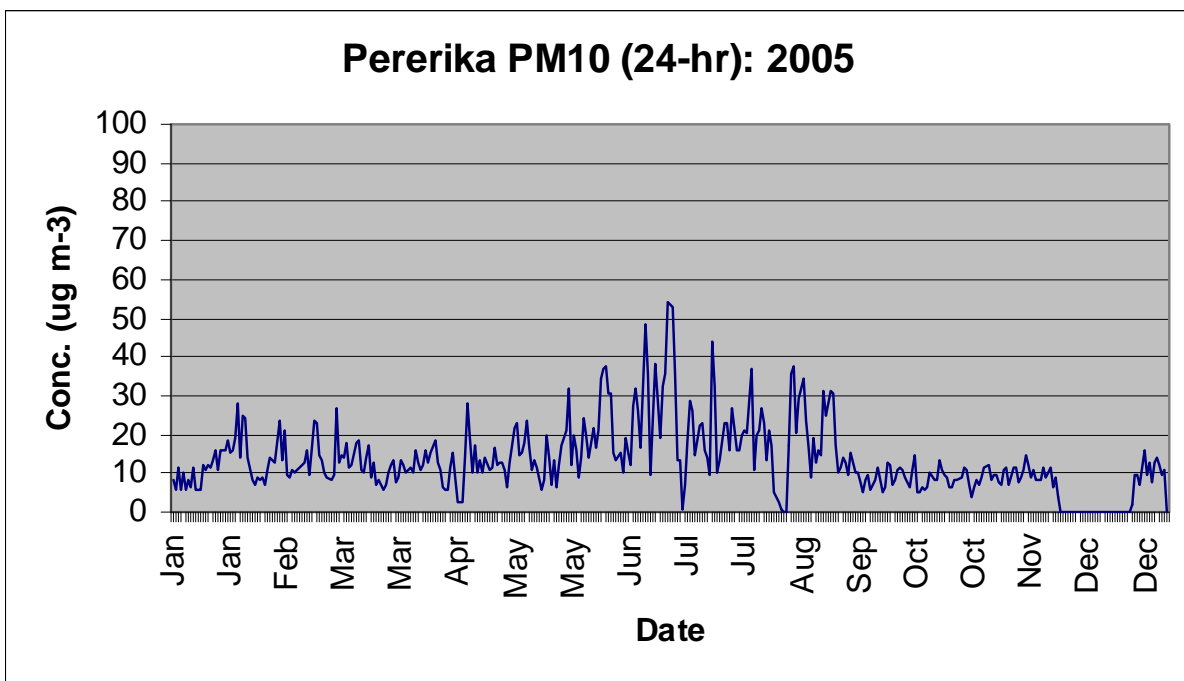
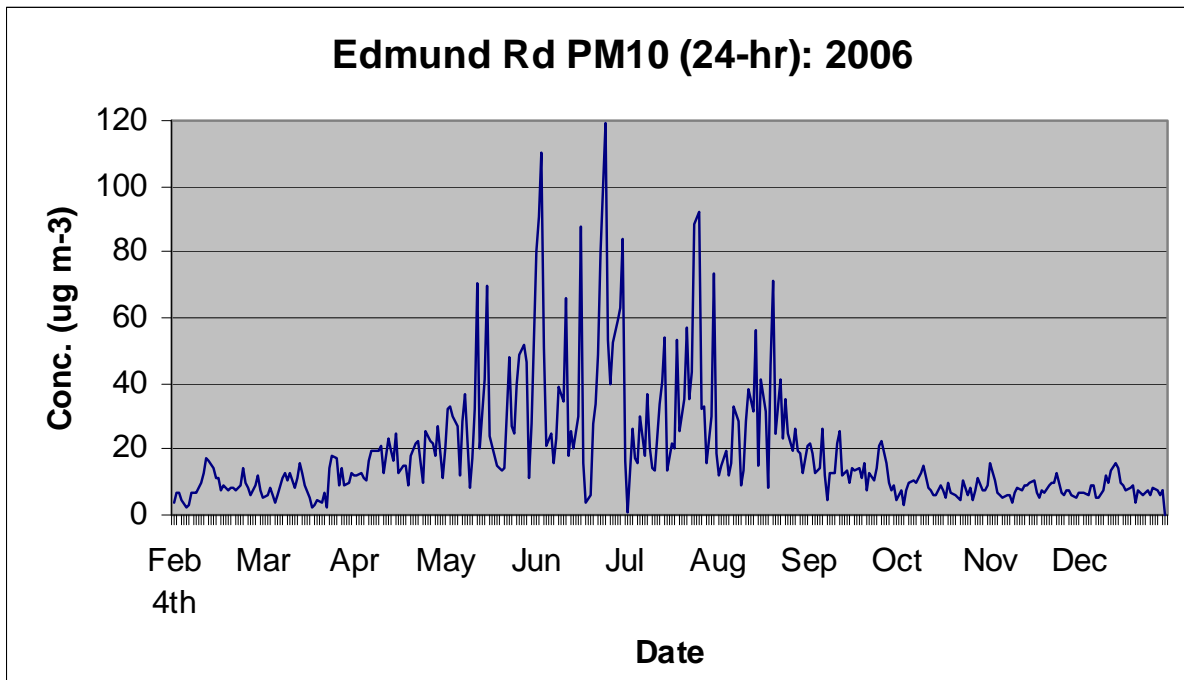


Figure 4.4



**Figure 4.5**

These monitoring records (and others not presented here) show that PM<sub>10</sub> exceedences do occur in Rotorua:-

1. Regularly in winter at Edmund Rd, sometimes well in excess of the standard.
2. Occasionally at Pererika St., usually in winter, but fewer in number and not as great as those at Edmund Rd.
3. No exceedences have been measured at Fenton St.

Based on this monitoring, it is likely that a significant portion of the suburban parts of the city currently experience PM<sub>10</sub> exceedences.

## 5. Monitoring Analysis

The monitored data can be further analysed to assess the effects of meteorology on the measured concentrations.

### Pollution roses - PM<sub>10</sub>

A more graphical analysis for assessing emissions effects is that of a 'pollution rose'. This is equivalent to a wind rose, where wind direction is correlated with PM<sub>10</sub> concentration rather than wind speed. Where both wind direction and PM<sub>10</sub> data have been forwarded by Environment Bay of Plenty, pollution roses are shown in Figures 5.1 and 5.2.

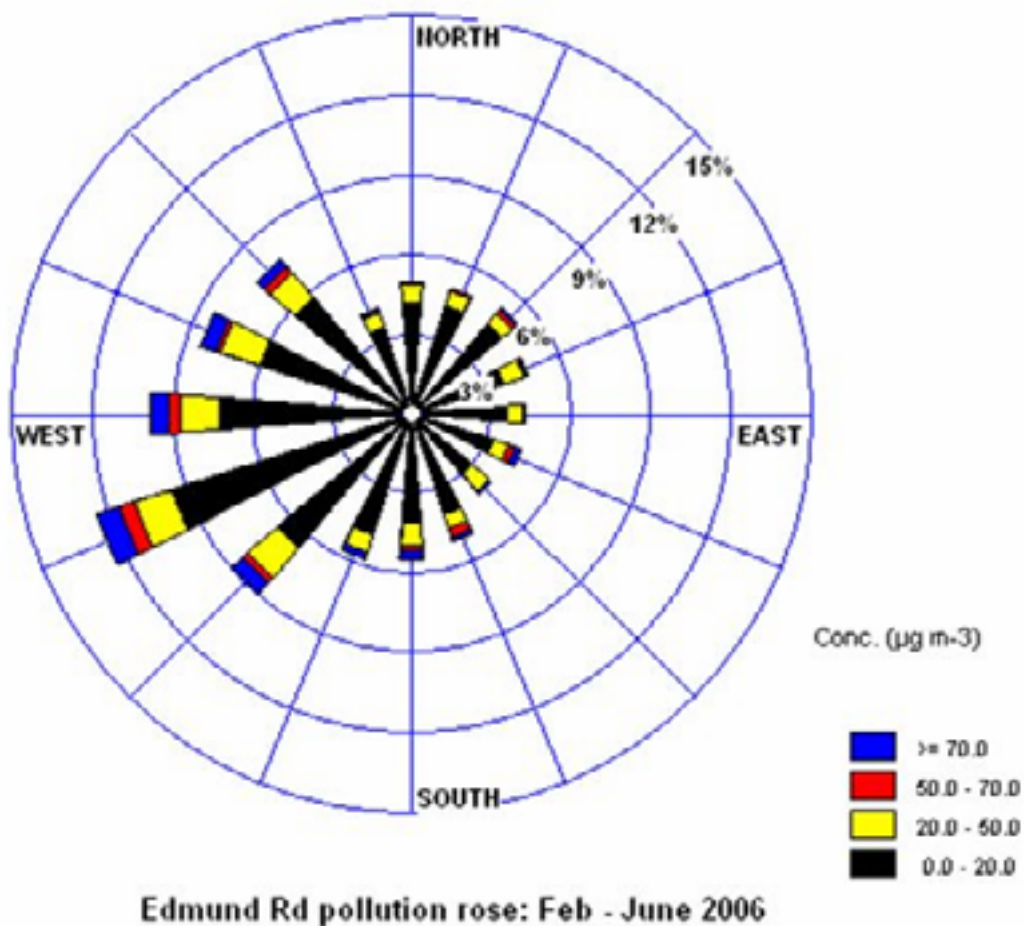


Figure 5.1 Pollution rose for Edmund St hourly PM<sub>10</sub>.

Figure 5.1 shows clearly that the majority of high concentrations occur in winds from the westerly and southwesterly quarters. This is in the direction of nearby housing, but more significantly is also the direction for night-time drainage flow winds from the hills down to the lake, and probably indicates some local re-directing of emissions from a larger area of housing.

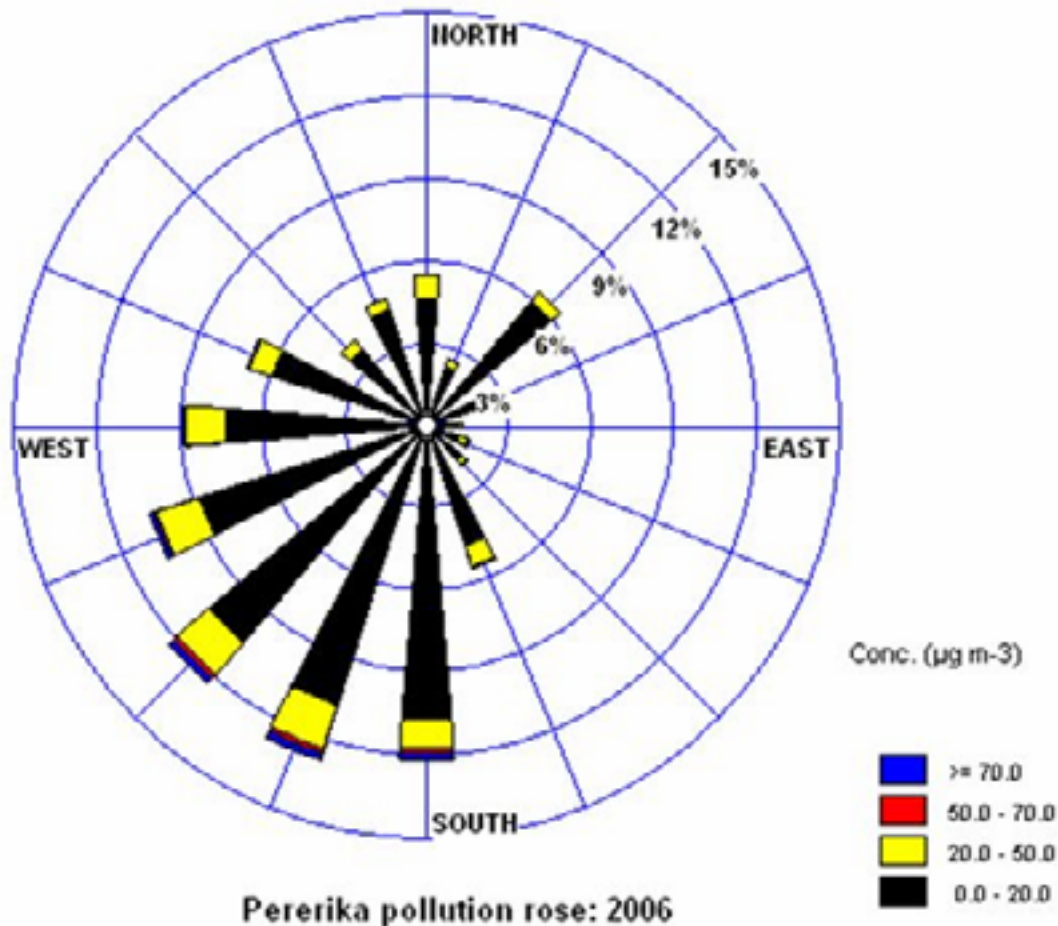


Figure 5.2 Pollution rose for Pererika St hourly  $\text{PM}_{10}$ .

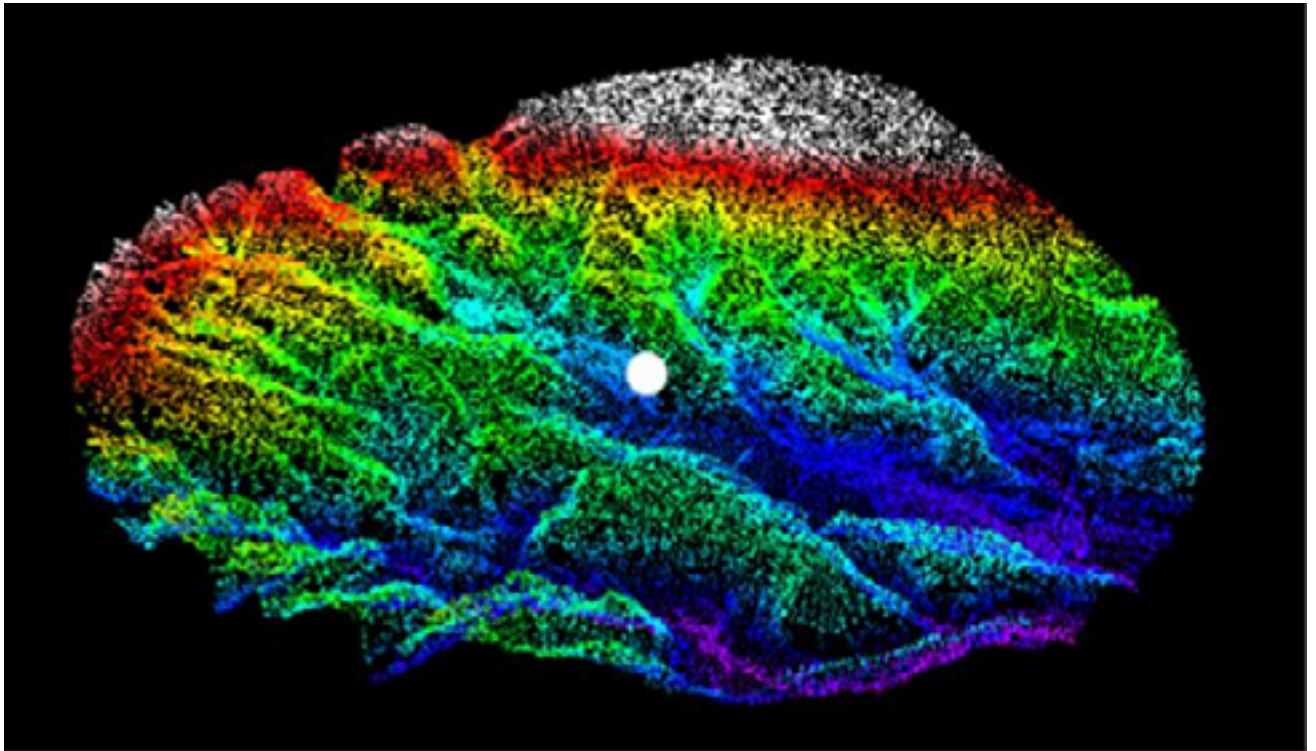
**Note on the interpretation of pollution roses:**

These are equivalent to wind roses, simply using the measured pollution instead of the wind speed. As for wind roses, when the wind speed is zero (or less than some threshold usually 0.5 m/s) the concept of wind direction is meaningless. The plots are still generated, since the wind direction sensor is still giving an output, but it may not be a true representation of the pollution direction. This can mean that some of the high pollution events being indicated from one direction may not have come from there. There is no practical way to account for this except by removing all cases of undefined wind direction, or reporting them separately as is done with 'calms' in wind roses. Thus pollution roses should be taken as indicative measures only, especially for the higher concentration values that will occur in calm periods.

The data also show some year-to-year variation. For instance in from 1998 to 2001 the predominate direction for  $\text{PM}_{10}$  pollution at Pererika St. was north to northeast. In 2002 to 2004, the sources were more even between the northeast and southwest. However in 2005 and 2006, the predominant sources have shifted to the southwest. This may be a complex climate effect, or may reflect a shift in the emissions sources.

Of note is the direction of air pollution sources when the hourly values are higher (above 70). These are predominately from the southwest, consistent with the drainage flow from the hills down to the lake, as seen at the Edmund Rd site. The effect is less at Pererika St. as it is further from the bulk of the houses emitting wood smoke, whereas the Edmund Rd site is closer to houses.

This drainage flow feature is illustrated in Figure 5.3 showing the digital terrain map for the Edmund Rd site. At night, stable airflows in light wind conditions will tend to drift down the local valley, carrying PM<sub>10</sub> emissions with them and dispersing only slowly.



**Figure 5.3** Digital terrain view of the Edmund Rd monitoring site in relation to valley features. (Figure courtesy of Environment Bay of Plenty).



## 6. Modelling Overview

### Airshed modelling approach

Airshed modelling is a complex procedure that has only become viable relatively recently because of the computing power required. The basic inputs are (a) a description of the terrain, including all topography and land use features, (b) a description of the meteorology, hour-by-hour for the period being modelled (usually a year), and (c) a description of the emissions of pollution, again hour-by-hour. These are all required in a digital form, with a spatial resolution of 250m.

The model is a collection of equations that calculate how the pollution is transported and dispersed by the movement of the winds around the terrain. These equations include terms for all of the variables that affect the pollution dispersion, including a wide range of weather parameters as well as any relevant chemical interactions in the air. They can also allow for pollution moving in and out of the domain, for material deposited to the surface, and even for recirculation of material (say being blown out to the lake during a southerly, and back in to town if the wind changes to northerly).

The terrain information is obtained from digital terrain models available from Terralink (the old Land and Survey Department of the government) and is considered very accurate and reliable.

The weather data needs to be generated. This is described in detail later (and in Appendix B), but a separate model is run to produce the meteorological file. This covers much of the North Island, since the weather in Rotorua is affected by conditions over a much larger area than just the town or the lake. As input to this meteorological model, data from automatic weather stations around the upper half of the North Island are used, along with data from the international global weather networks. The weather data generated is checked against monitoring records from local weather stations, and is generally reliable, provided enough care is taken with its preparation.

The emissions information comes from the Air Pollution Emissions Inventory developed by Environment Bay of Plenty. The modelling can be conducted on any emitted pollutant, although here the focus is on  $PM_{10}$ , which is known to exceed the standards from the ambient monitoring. Concentrations of all other pollutants are not as high relative to the standards.

The model calculation runs in three dimensions, for each hour of the period. This can take many hours, even days, of computer time. The outputs generated are air pollution concentration values at each point in the domain, for each hour in the period. The models also produce this data at several levels in the atmosphere (although values above ground level are not used here). The output files for the Rotorua modelling are 65Mb each – and there are several. These files are processed, and where required, averaged to 24-hour values (or annual values if required) from the basic 1-hour results.

The modelling has been conducted separately for each of the three major sources – domestic, transport and industry. This is partially because of expediency in reducing the turnaround time for results, but also because it can be instructive to see independently the effects due to the different sources.

The final step, is to combine all these modelling results together, add in an appropriate value for the 'background' (that is the pollution values that exist naturally due to background

sources such as dust, pollen, rural burning etc – these are usually quite small in relation to the effects from the city's emissions, but shouldn't be ignored) and produce a final map of the air pollution feature of interest. There are any number of plots that can be made, but of primary interest here are just two quantities (1) the peak concentration occurring (particularly in relationship to the relevant guideline or standard), and (2) the frequency of exceedence of any guideline or standard.

## Modelling systems used

Assessments of the airshed effects of various air discharge sources via airshed and dispersion modelling have recently started to be undertaken with more complex non-steady state models such as Calpuff. Previous dispersion modelling in New Zealand has largely been undertaken with the steady state models such as Ausplume and ISC3. However recent advances in technology have allowed the use of these more advanced non-steady state models for complex environments. The Good Practice Guide for Atmospheric Modelling (Ministry for the Environment, 2002) has recommended the use of complex models (Recommendation No 7) when: -

- Meteorological conditions vary across the modelling domain,
- Modelling domain incorporates complex terrain
- Pollutants accumulate in calm conditions and re-circulation can occur,
- Frequent low wind speed or calm conditions occur,
- Chemical transformations between pollutants may occur,
- Appropriate meteorological data are available to drive them.

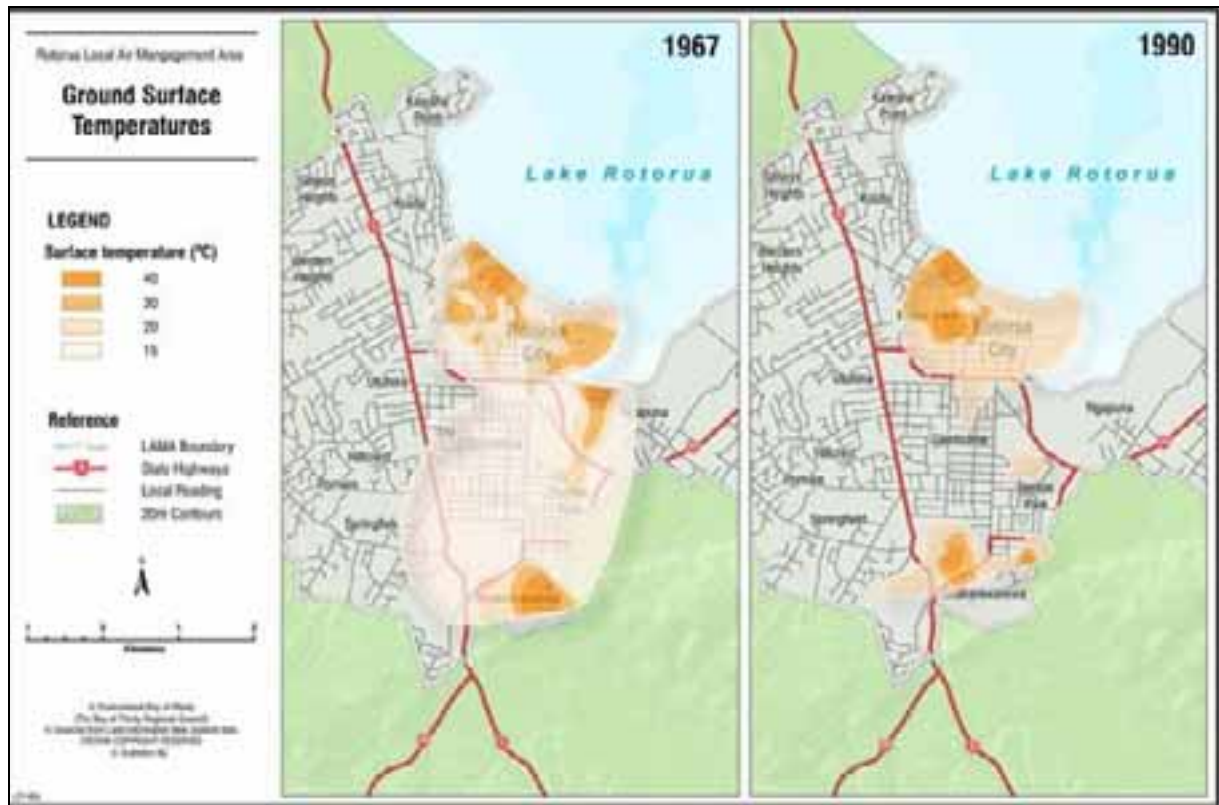
Due to the complex meteorological conditions in the Rotorua area it was necessary to use a non-steady state complex dispersion model. The dispersion model used in this study is Calpuff, which is a Gaussian puff dispersion model and is approved for regulatory uses and distributed by USEPA. Calpuff is run with a non-steady state 3-D meteorological data set produced by the sub-model Calmet. Run in this mode, Calpuff allows for more complex fumigation and mountain-valley slope flows, calm conditions and variation of the meteorology over the modelling domain. A more detailed description of the model used is given in Appendix B.

## Terrain features

The terrain and land use factors are important to know as they affect the meteorology and dispersion. The wind flows do depend on whether the surface terrain is grass, lake, forest, houses, etc – and the modelling takes full account of all of these factors. The modelling also needs to take account of other features than can affect dispersion, such as the surface temperature. This is calculated based on the land use type, the season and time of day.

It has been suggested that Rotorua's geothermal fields may have an effect on the meteorology and modelling. This is not unreasonable, since they are a source of heat and steam that may affect the atmospheric behaviour above the city. This is possibly the first time this question has ever been raised, given that in this regard Rotorua is unique in the world, and it is doubtful that any similar degree of airshed modelling has been done in such a geothermally active area.

Maps of the surface temperature were produced in the Rotorua Emissions Inventory, and are shown in Figure 6.1. These show that parts of the city can experience ground temperatures of over 40°C.



**Figure 6.1 Surface temperatures due to geothermal activity (from the Rotorua Emissions Inventory)**

The meteorological model does not have to take account of ground surface features and temperature, since these affect convection and hence dispersion. The seasonal solar heating differences are included, as are the day-night differences. Although not specifically confirmed, it is likely that most of the time any small scale heating of the surface or air by geothermal bores will be swamped by the normal diurnal and seasonal patterns, or by simple weather factors such as whether it's cloudy or not. However on cold nights, such surface heating may result in additional levels of dispersion. A fully featured model would have to take account of these temperature fields, but this has not been done here.

As is shown later in this report, the highest levels of air pollution occur in the western and southwestern parts of the city (and to some extent in the northwestern and eastern parts), where wood burning for home heating is prevalent. The localised geothermal heating is unlikely to affect these areas, and thus unlikely to have any effect on the modelling of high pollution values. This surface heating may well have an effect on reducing air pollution concentrations in those parts of the city where it occurs, but these are not areas with high emissions, and are not subject to high ambient concentrations.

This topic may warrant further investigation, but it is unlikely to significantly affect the modelling results presented here.

## Meteorology

Meteorology forms the single biggest effect on the dispersion of contaminants from sources. If the meteorology is well characterised for a particular domain, then there will be a reasonable amount of confidence in the model outputs. The present modelling assessment was undertaken for the year 2001, simply because some earlier results were available for validation.

The meteorological data sets were developed using the Calmet model which is the meteorological processor of the Calpuff air dispersion model. Input data of monitored data from upper air twice-daily profiles from Whenuapai and Paraparaumu Airports, and 20 surface weather stations that recorded hourly meteorological observations in the Waikato-Bay of Plenty region were used (see Table B.1 in Appendix B).

## Calmet meteorological model

Abbreviated summary Calmet model inputs are as follows:

- Upper air radiosonde data (Whenuapai , Paraparaumu , 00H00 and 12H00 to 500 hPa)
- Hourly surface meteorological data (20 automatic weather stations AWS) – wind speed, wind direction, temperature, relative humidity, pressure, rainfall and cloud heights. See Table 5.1.
- Terrain data (LINZ data at 250 m resolution)
- Landuse data (LINZ data at 500 m resolution).
- Cell size of 500 m
- Grid domain of 33 km (Eastings) and 22 km (Northings)
- 10 vertical levels (0,20,50,100,200,400,600,800,1000,2000,3000 m).

## Calpuff dispersion model

Parameters used in Calpuff include the following: -

- Domain size of 16 km (Eastings) and 16 km (Northings)
- Grid resolution of 250 m
- Tracer mode
- PM<sub>10</sub> as the primary pollutant
- Turbulence coefficients determined by micrometeorology (Calmet)
- Run for partial plume penetration mode ON
- 64 x 64 grid receptors (250 metre grid squares)
- Building downwash ON (estimate building size building 100 m long, 45 m wide, 10 m high)
- PDF function ON

## Model set up

An estimate of the Calmet and Calpuff model domains is shown in Figure 6.2.

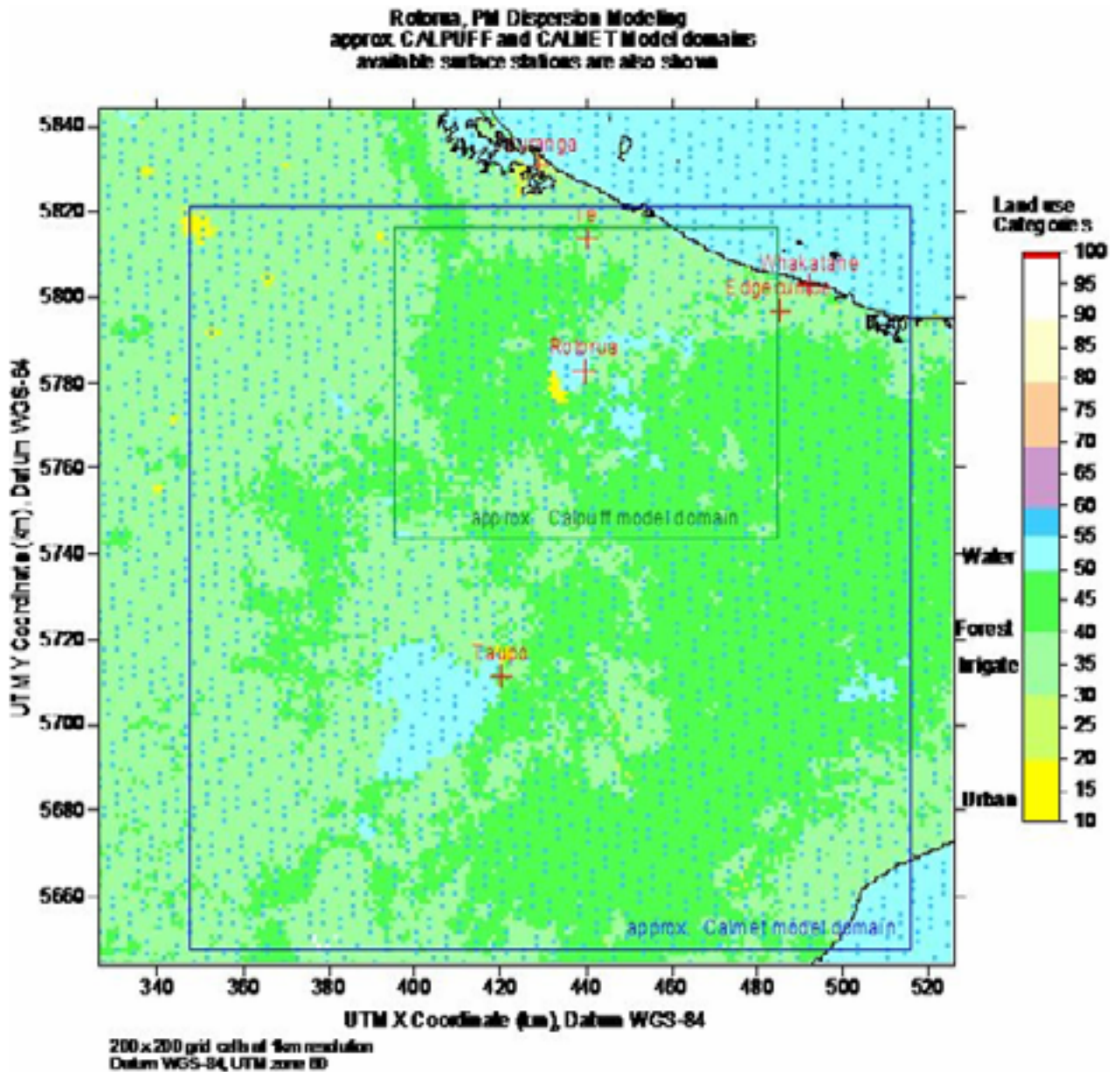


Figure 6.2 Approximate Calpuff and Calmet model domains used in the dispersion modelling.

## Meteorological model results

The Calmet model has been run for the year 2001 and produced the required detailed hourly meteorological field over the domain. As a first order validation, a comparison is made between the model output and the measurements from the Pererika site in central Rotorua (NB. The data from this site was not used to initialise the model, so this is a perfectly independent and valid comparison).

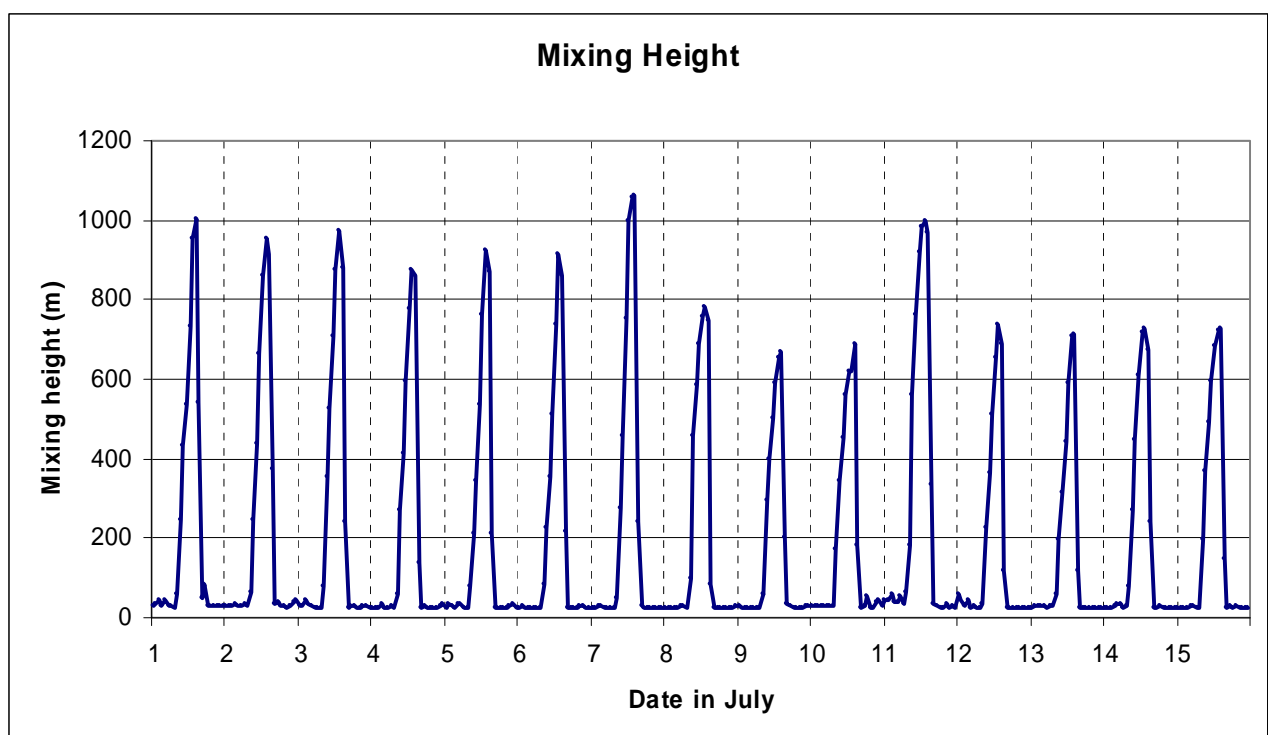
## Box model

A secondary part of the project has employed a simplified box model to assess the relationships between emissions and air pollution. This model was developed for use in Christchurch, and has also been applied in Nelson. Spreadsheet based, it takes a very simplified approach by defining a box parcel above an area source of emissions and calculating how the surface emissions affect the total concentration within the box. It can only work in calms or very light winds, and some assumptions about meteorological conditions need to be made. However it is ideal for examining worst case conditions, and this has been done here using a typical calm winter night, and emission profiles for a high emissions 250m x 250m box near the Edmund St site.

It is also ideal for getting a simplified idea of reductions needed to achieve the standards, as well as a good method for providing a reality check on the more detail airshed modelling. It cannot give the detailed time and space patterns of the airshed modelling.

## Inversions

A major cause of high pollution is the occurrence of a winter time inversion over the city. "Inversion" can be a misleading term, with a more correct one being the "mixing depth" – the height to which pollution emitted at the surface can disperse. This phenomenon is well known as the major reason some South Island towns (such as Christchurch) experience very high pollution levels. Model outputs of the day-to-day variation in the mixing depths are shown in Figure 6.3.



**Figure 6.3** Depth of the inversion layer, Rotorua, July 2001.

The noticeable feature of these results is the regular, rapid, and severe collapse of the mixing layer every afternoon at 3pm to 4pm – just when wood fires are being lit. This 'inversion' creates a trap for air pollution on many nights in winter. Its break up in the

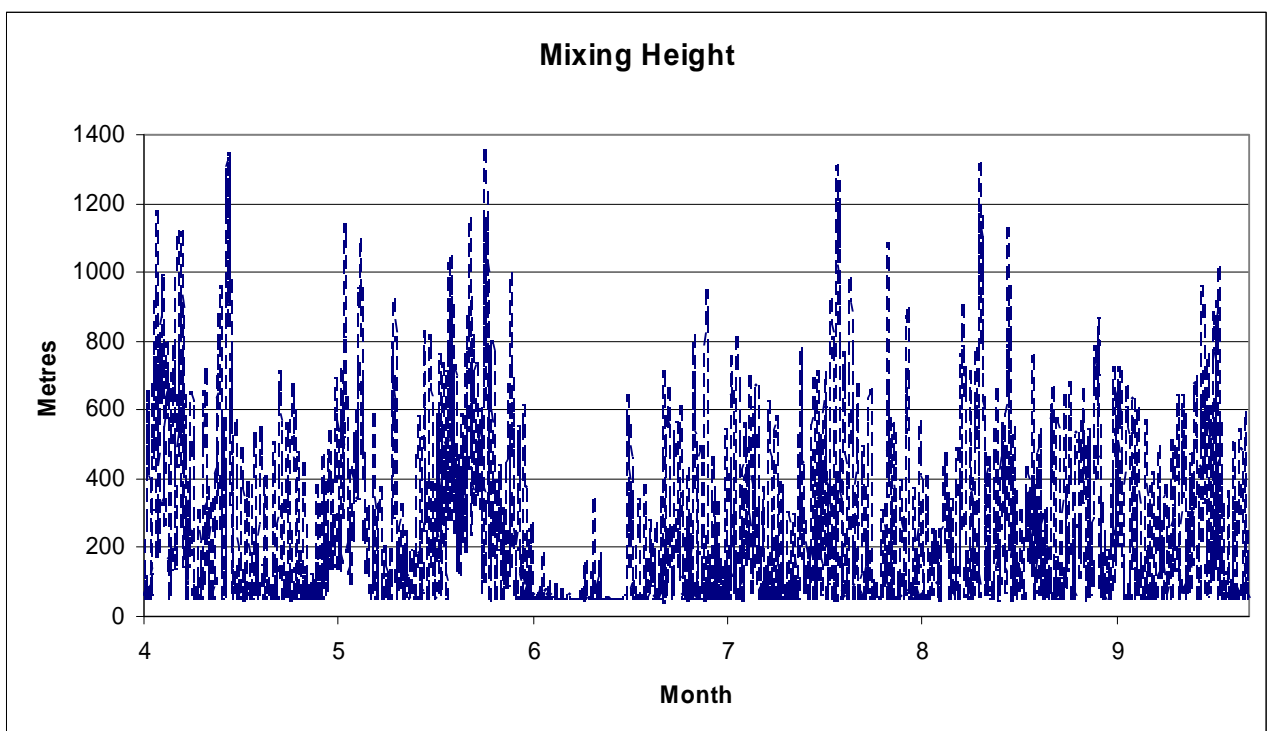


morning, along with a slight increase in wind speeds, effectively clears the city each day. Without this, a situation could arise where high pollution from the previous night could stay around and lead to very high concentrations (as occurs occasionally in other places).

A more extensive period is shown in Figure 6.4, for the whole of winter. This is shown to illustrate two features of relevance to air pollution occurrences.

There are two periods – in early May, and later in May – where the mixing height is almost never less than 150m. These are likely to be windy periods, where even at night the atmosphere is turbulent and any pollution emissions will be dispersed rapidly.

In contrast there is a period in early June where the opposite occurs – the mixing height rarely exceeds 100m, and is regularly at or below 50m. These are likely to be cool, calm conditions, where pollution emitted does not disperse and can build up to exceedance levels over much of the city.



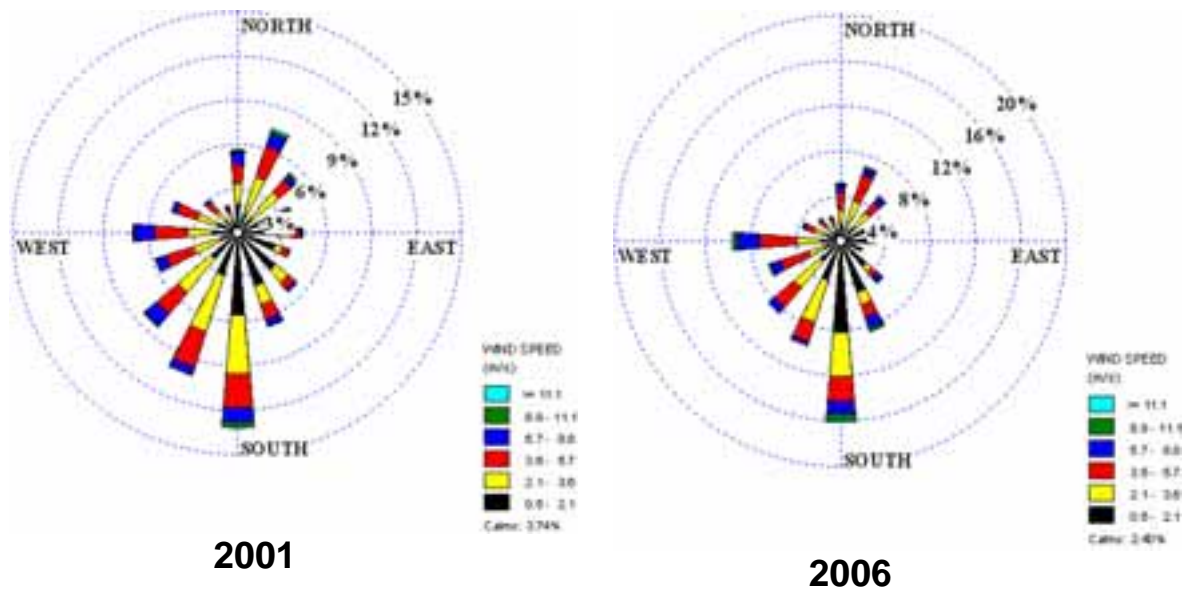
**Figure 6.4** Depth of the inversion layer, Rotorua, through winter of 2001.

Note that some of these inversion features described above may be specific to the particular year of meteorology – 2001. Some features may be slightly different from year to year (Discussed in the next section).

## **Representativeness of the meteorological data used**

The modelling has been carried out using emissions from the 2006 emissions inventory (the reference year being 2005) but meteorology from the 2001 year. The main reason was that 2001 meteorological data was available and had undergone a degree of quality control. A fundamental assumption is thus that the 2001 meteorology is representative of the general meteorology across the region, and that year-to-year differences do not bias the results.

Some additional modelling has been conducted using the 2006 meteorological data – which is now available. This has necessitated constructing complete new data files, using data from stations all over the North Island (as described above for 2001). The modelling comparison is shown later, but it is instructive to examine any differences between the actual monitored data from the Pererika St meteorological monitoring station. A full analysis is given in Appendix C, but the key features can be seen in the summary wind roses shown in Figure 6.5.



**Figure 6.5 Meteorological monitoring summary, 2001 vs. 2006. (Data from Pererika St for May, June, July, August, and September only).**

The comparison shows that the meteorology in Rotorua in 2001 and 2006 was remarkably similar. Only the winter-time data has been used in this comparison, since this is the period of greatest interest (e.g. high levels of air pollution in Rotorua do not occur outside of this period). The key wind directions and wind strengths show a considerable degree of consistency between the two years. All of the summary statistics (presented in Appendix C) also show a high degree of consistency.

Only one feature shows a slight difference, and that is the number of calms (hourly wind speed < 0.5 m/s) was slightly lower in 2006 (2.4%) vs. 2001 (3.7%). This can affect the modelling results since higher pollution values tend to occur in calm periods.

Overall, the degree of consistency in the meteorology between 2001 and 2006 is strong, and if anything the 2001 year is probably slightly better as it shows a higher number of calms.

## 7. Airshed Model Results – PM<sub>10</sub>

Airshed model results are given according to source category. The model runs are based on a full year of meteorological data, but because of the time taken to run the model (several days of computer time with all sources), the model runs were done on parts of the year:-

- Domestic sources – 4 months of winter (May, June July, August) – they are negligible at other times
- Transport sources – two months in winter (June, July) and two months in summer (January, February)
- Industrial sources – full year (the model run times are short since there are fewer sources)

These restrictions do not affect the model results, since in each case the peak expected values are covered (e.g. domestic peaks are all in winter). Similarly the exceedences are covered – all the domestic ones are in winter, the industrial discharges are assessed throughout the year and the transport discharges are not high enough to cause exceedences.

### Domestic emissions – 24 Hour

The first model output shown in Figure 7.1a is the maximum 24-hour PM<sub>10</sub> concentration due to domestic heating emissions. Figure 7.1a shows the pattern of PM<sub>10</sub> concentrations across the region on a worst case day in June (averages taken mid-night to mid-night as per the Ministry for the Environment guidelines) due to domestic heating emissions. This shows peak values in the suburbs to the west and southwest of the city, where domestic heating emissions are high. There are also areas of high concentrations in the northwest and east of the city, again in locations where emissions are high. The highest concentration modelled is 96  $\mu\text{g m}^{-3}$ .

There are two areas where concentrations peak (over 70  $\mu\text{g m}^{-3}$ ). These are aligned along the shallow stream valleys in the west and southwest of the city, as indicated earlier in the relief map (Figure 5.3). The Edmund St monitoring site is located in one of these areas, and will thus indicate peak events. One feature of this result is that the peak concentrations are not necessarily completely aligned to the peak emissions areas. This is because of the terrain and light wind airflows that tend to move the pollution emissions downslope and concentrate in the shallow valleys and towards the lake. Another feature is that elevated concentrations can occur on the edges of the low hills surrounding the city, which seems to be occurring on the eastern side of the city. This happens when there might be a slight wind drift towards the hills and smoke from chimneys can get trapped up against the hillside.

### Comparison between 2001 and 2006

The modelling for domestic solid fuel emissions has been conducted again using the 2006 meteorological file. As discussed above, the 2006 year had fewer calm periods than 2001, possibly leading to lower air pollution concentrations. The worst case (highest) hourly PM<sub>10</sub> concentrations are shown in Figure 7.1b.

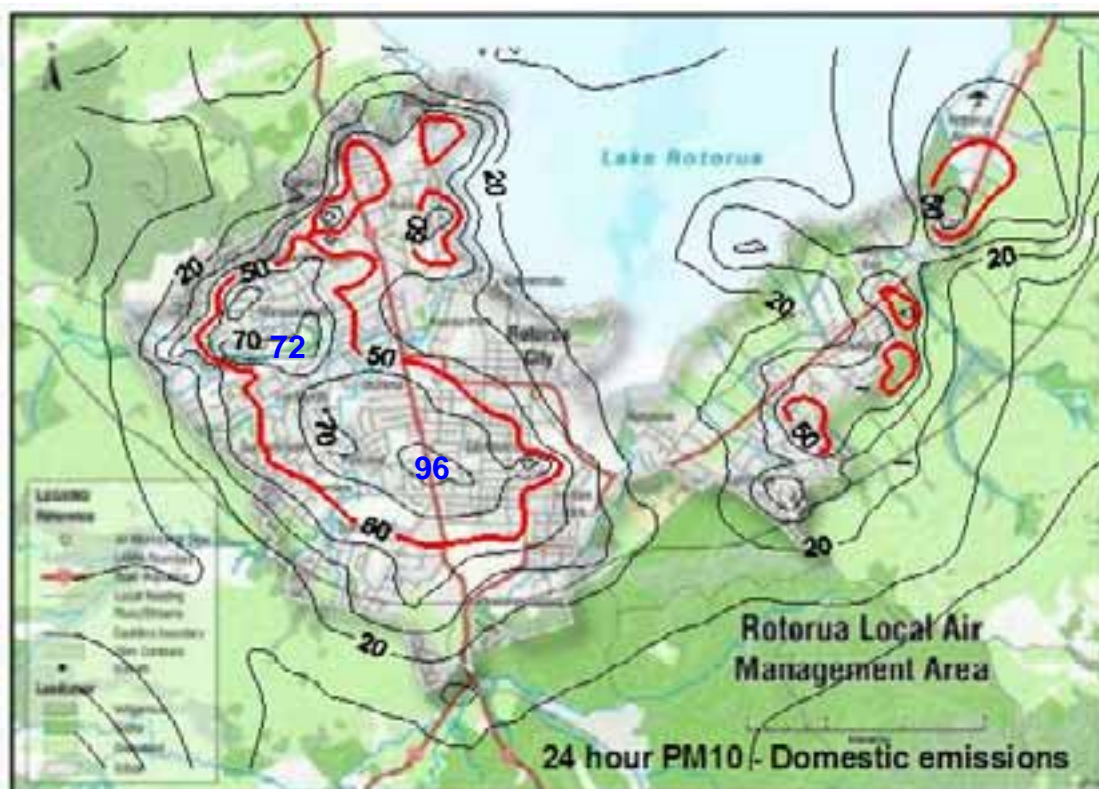


Figure 7.1a The spatial pattern of 24-hour  $PM_{10}$  concentrations across Rotorua, from domestic heating emissions, the worst case winter results, 2001.



Figure 7.1b The spatial pattern of 24-hour  $PM_{10}$  concentrations across Rotorua, from domestic heating emissions, the worst case winter results, 2006.

Despite the meteorological analysis having shown little difference in the general winds between 2001 and 2006, the modelling results do show some differences:-

- 2006 has a slightly different pattern of ambient concentrations with broad higher concentrations in the western and southwestern parts of the city, and lower concentrations in the east, over those in 2001.
- 2006 has slightly lower peak values, with the modelled maximum being  $87 \mu\text{g m}^{-3}$  compared with the  $96 \mu\text{g m}^{-3}$  in 2006
- This peak value occurs at a slightly different location.

These differences are no doubt due to quite subtle variations in the meteorology, particularly on the worst case night time conditions when the peaks occur.

These modelled results should not be compared directly to the monitoring results since (a) they are grid averages over 250m, whereas the monitoring represents single point values and (b) the actual hourly emissions are unlikely to be precisely the same as those given in the emission inventory and used in the modelling.

Overall, this result gives some confidence that the 2001 year used for modelling is slightly more conservative than the 2006 year, and it has been used in the further modelling described below.



## Domestic emissions – Exceedences

The number of days in the year that the  $50 \mu\text{g m}^{-3}$  24-hour concentration is exceeded due to domestic emissions is shown in Figure 7.2. Note that this is for the 2006 year.



**Figure 7.2** The spatial pattern of 24-hour PM<sub>10</sub> exceedences across Rotorua, from domestic emissions, the worst case results, 2006. (Local peak values also indicated.)

Figure 7.2 shows that exceedences of the 24-hour PM<sub>10</sub> standard occur extensively in the west and southwest of the city.

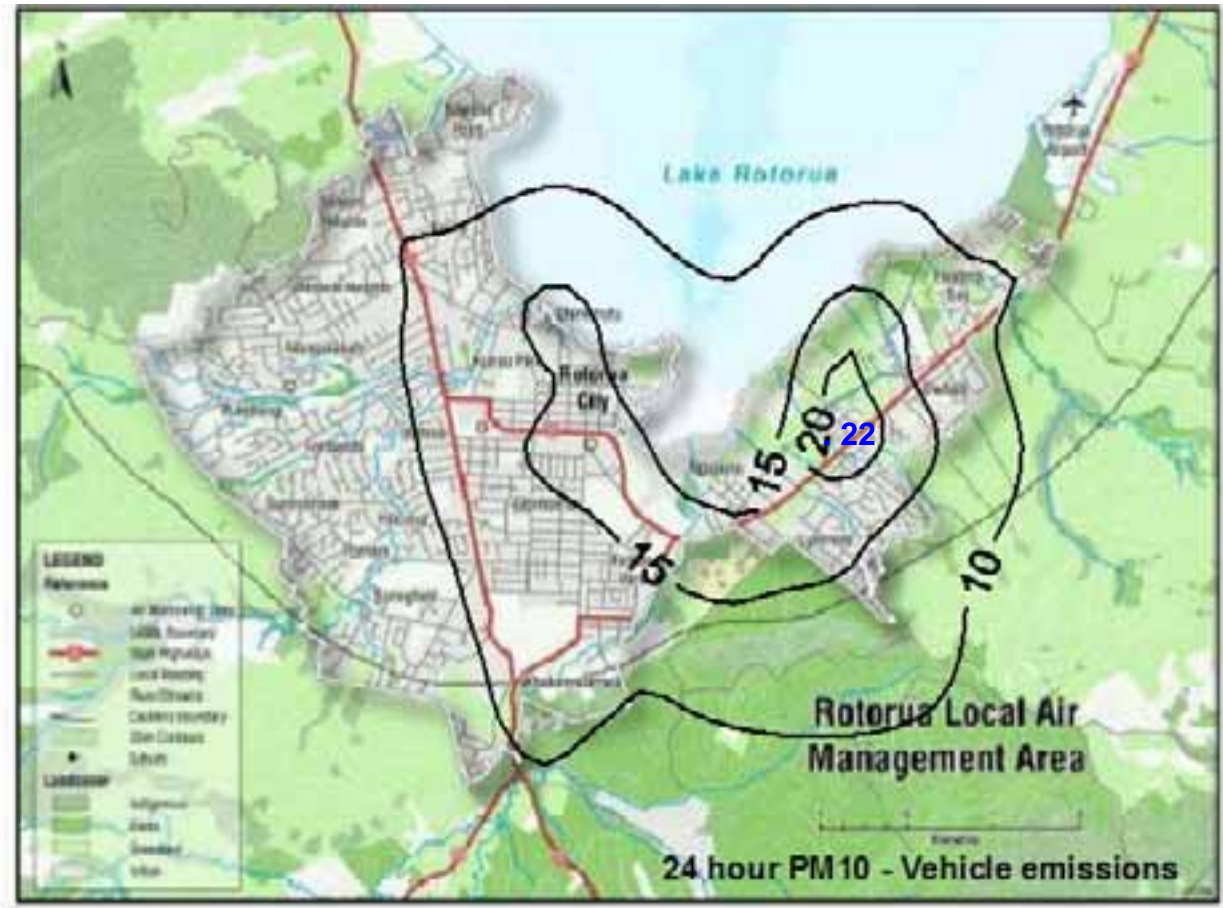
The result is broadly consistent with the monitoring, with multiple exceedences at Edmund Rd., and occasional exceedences at Pererika St.

This modelling result show exceedences on up to 17 days a year, however actual monitored exceedence rates at specific locations (such as Edmund Rd.) may be greater. This is due to the model resolution, which at 250m may not be fine enough to identify very localised 'hot-spots' where PM<sub>10</sub> concentrations may be higher due to a particularly high density of emission sources on a scale finer than 250m. This is likely to be the situation around the Edmund St. monitoring site, and perhaps in other places.



## Vehicle emissions – 24 Hour

The second model output shown in Figure 7.3 is the maximum 24-hour PM<sub>10</sub> concentration due to vehicle emissions.



**Figure 7.3** The spatial pattern of 24-hour PM<sub>10</sub> concentrations across Rotorua, from vehicle emissions, the worst case winter results, 2001. (Local peak values also indicated.)

Figure 7.3 shows the pattern of PM<sub>10</sub> concentrations across the region on a worst case day in June due to vehicle emissions. This shows peak values along the major roadways particularly SH5 in the northwestern part of the city. The highest concentrations occur around the Racecourse, in upper Fenton St, and around the industrial area, again reflecting the concentration of traffic. .

The absolute numbers are considerably lower than those due to home heating emissions, with peaks of around 22 µg m<sup>-3</sup>, occurring around the busy eastern route out of the city. (Note that very localised areas – such as within a few metres of a busy roadway – will have higher exposure levels. These are not resolved in the airshed modelling as they will only extend for 10-20m.

## Vehicle emissions – Exceedences

There are no exceedences of the standard due to vehicle emissions alone.

## Industrial emissions – 24 Hour

The third model output shown in Figure 7.4 is the maximum 24-hour PM<sub>10</sub> concentration due to industrial emissions.



**Figure 7.4** The spatial pattern of 24-hour PM<sub>10</sub> concentrations across Rotorua, from industrial emissions, the worst case winter results, 2001. (Local peak values also indicated.)

Figure 7.4 shows that 24-hour PM<sub>10</sub> concentrations due to industrial emissions are not particularly high, with the peak being 29 µg m<sup>-3</sup>. The modelled ground level concentrations are almost entirely due to two large wood processing facilities in the eastern area. Numerous smaller dischargers are included in the modelling, but do not result in 24-hour concentrations above 5 µg m<sup>-3</sup>. This modelling result is based on the maximum permitted emissions rate for the consented industries.

## Industrial emissions – Exceedences

There are no exceedences of the standard due to industrial emissions alone. Very localised higher concentrations may occur that do not show up on the 250m modelling grid scale.

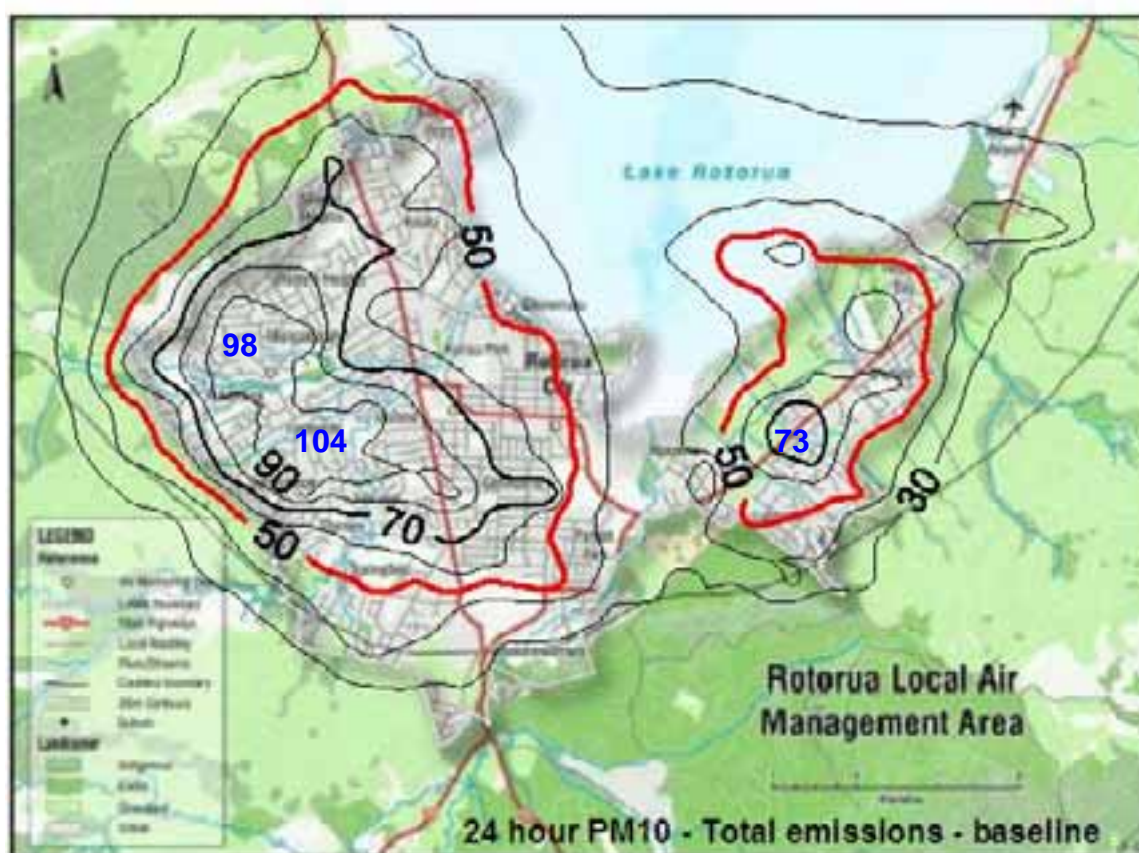
## Background

The final basic model output needs to include an estimate for background concentrations. That is PM<sub>10</sub> due to sources other than the three main ones considered so far – domestic, vehicle and industrial. These sources will typically be wind blown dust, rural burning, and emissions from various agricultural activities. A value of 5 µg m<sup>-3</sup> has been assumed across the whole of the area.



## Total emissions

The final step in the process is to add all of these sources together, shown in Figure 7.5.



**Figure 7.5** The spatial pattern of 24-hour PM<sub>10</sub> concentrations across Rotorua, from total emissions, the worst case results, 2001. (Local peak values also indicated.)

Figure 7.5 shows the worst case day expected, due to emissions from all sources. These modelling results are consistent with the monitoring results from the three sites in the city. The Edmund Rd. site has shown values over  $100 \mu\text{g m}^{-3}$ , the Pererika St. site shows values above  $50 \mu\text{g m}^{-3}$ , and the Fenton Rd. site does not show any values above  $50 \mu\text{g m}^{-3}$ . These are all broadly consistent with what is shown here.

These model results can be compared in detail with the monitoring statistics, but with caution. For instance the peak values measured at Edmund Rd in the winter of 2007 are up to  $120 \mu\text{g m}^{-3}$ , slightly above the result shown here. This is probably due to two factors:-

1. The airshed model produces a concentration that is representative over the area of the size of its basic grid cell –  $250\text{m} \times 250\text{m}$ . It is entirely conceivable that there can be ‘hot-spots’ within this areas where concentrations can be higher. This is a natural consequence of the averaging used by the model, and cannot be fully resolved unless the modelling is conducted at a finer and finer resolution. This is theoretically possible, but would take years, rather than days, of computer time to run.
2. This modelling result is for 2001, whereas the higher Edmund Rd monitoring has occurred in 2007. Both the weather and emissions are almost certainly different for these two years. Some experience in other areas where modelling has been carried out, in Christchurch for instance, show that differences in peak concentrations from year-to-year can be as high as  $\pm 50\%$ .

## Total emissions – Exceedences

The number of days in the year that the  $50 \mu\text{g m}^{-3}$  24-hour concentration is exceeded due to all of the emissions is shown in Figure 7.6. Note that this is for the 2006 year.



**Figure 7.6** The spatial pattern of 24-hour PM<sub>10</sub> exceedences across Rotorua, from total emissions, the worst case results, 2006. (Local peak values also indicated.)

Figure 7.6 shows that there widespread areas of the city that can – and do – experience exceedences. The peak rate shown by the modelling is for 23 days per year, in the vicinity of the Edmund Rd monitoring site. This is consistent with the monitoring data which showed 24 exceedences in 2006 and 26 in 2007.

There are also a number of exceedences in the southeastern part of the city (up to 16 days per year), and a few in the eastern suburbs (up to 6 days per year).



## 8. Airshed Model Results – Other

Thus far the modelling has focused entirely on PM<sub>10</sub> –since it is known from the monitoring that there are exceedences of the standard, and it is likely that this is the key contaminant needing mitigation.

However other contaminants are emitted (see the Rotorua Emissions Inventory, 2006 for a full discussion). The airshed model can be applied to any of these contaminants since all of the necessary emissions data are available.

### NOx

At this stage, only one other contaminant has been explicitly modelled – the NOx emissions from vehicles. From an examination of the data in the emissions inventory it is likely that this will be the ‘next worst’ air contaminant after PM<sub>10</sub>. In addition, only transport emissions have been modelled, since these comprise 90% of the NOx emissions in the city (i.e. the contributions from domestic and industrial sources will make very little difference to the result, and there is no natural background). The result for the worst case day (in July) is shown in Figure 8.1. The peak 1-hour value is less than 20  $\mu\text{g m}^{-3}$ . This can be compared to the 1-hour standard of 200  $\mu\text{g m}^{-3}$ . This shows that nowhere in Rotorua, at any time, does the NO<sub>2</sub> concentration get higher than 10% of the standard.

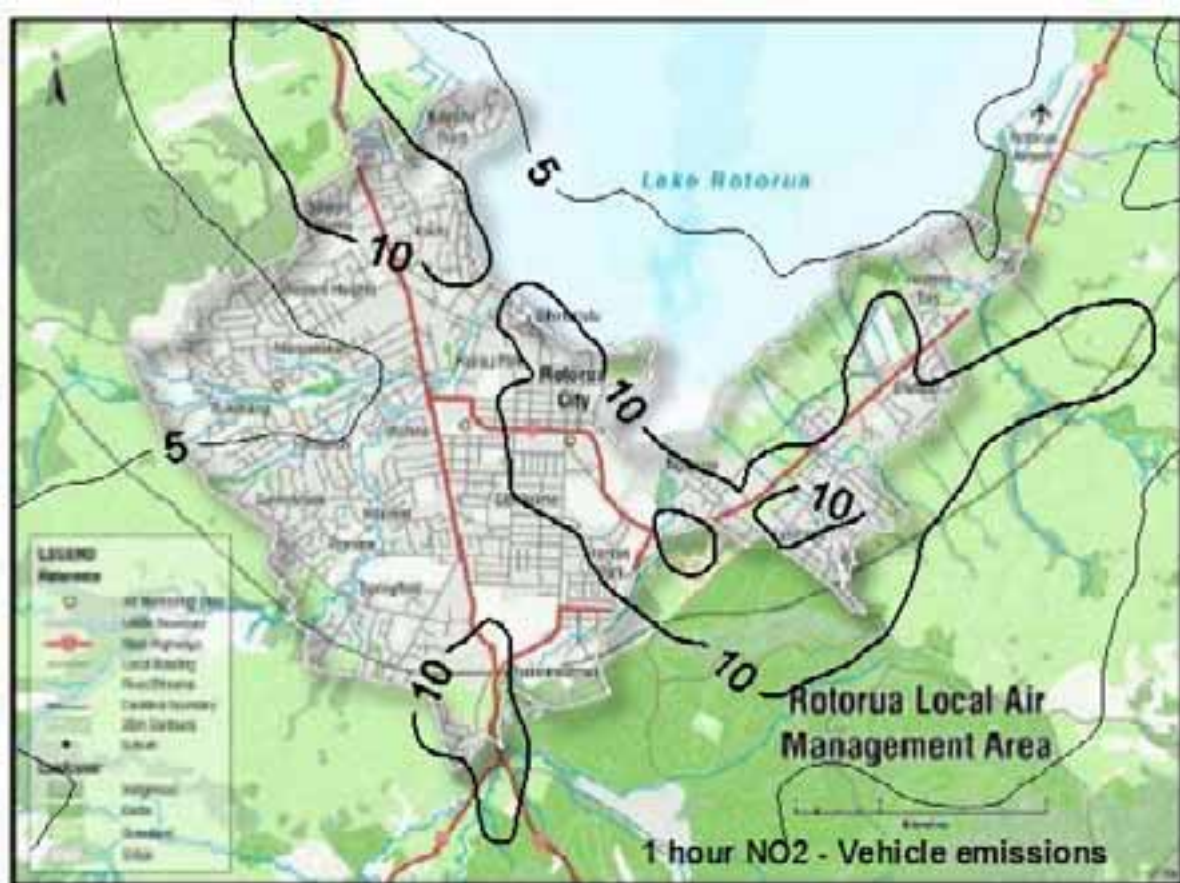


Figure 8.1 The spatial pattern of 1-hour NO<sub>2</sub> concentrations across Rotorua, from vehicle emissions, the worst case winter results, 2001.

Note that even this result for NO<sub>2</sub> could be regarded as very conservative. NO<sub>2</sub> forms from the conversion of the NO<sub>x</sub> emitted over a period of hours. The complex chemistry involved can be modelled, but needs more data than are available (i.e. ozone values). The approach taken here is just to use the maximum theoretical rate. This is unlikely to ever happen, and actual NO<sub>2</sub> concentrations – if ever monitored – will be even lower than those shown.

## SO<sub>2</sub>

Another contaminant covered by standards is SO<sub>2</sub>. According to the emissions inventory, the SO<sub>2</sub> emissions are relatively minor:-

- from domestic heating, about 3% of the mass emissions of PM<sub>10</sub>
- from industry about 50%, and
- from transport, essentially zero (although there is still some sulphur in diesel fuel)

Both PM<sub>10</sub> and SO<sub>2</sub> behave as gases, so a broad assessment can be made examining the ratio of the two.

On this basis, the peak 24 hour concentrations of SO<sub>2</sub> due to domestic emissions will be of the order of 2-3 µg m<sup>-3</sup> and these will occur in the western and southwestern areas of the city

The peak values due to industrial emissions are of the order of 15 µg m<sup>-3</sup>, and these only occur for a small area of about 500m x 500m surrounding the two major industries. At further distances of 1-2 kilometres they fall to 1-2 µg m<sup>-3</sup>, and are essentially zero over much of the central and western parts of the city.

These peak values of SO<sub>2</sub> are unlikely to be a cause of concern, given the current guideline value for 24-hours is 125 µg m<sup>-3</sup> (the standard is only for 1-hour), and even the newly revised WHO 24-hour guideline is 25 µg m<sup>-3</sup>. The worst case SO<sub>2</sub> values anywhere in Rotorua are well within the NZ guidelines and standards, and also well within the new WHO guidelines.

## CO

A similar analysis can be conducted for carbon monoxide. Relative to PM<sub>10</sub>:-

- from domestic heating, about 9 times of the mass emissions of PM<sub>10</sub>
- from industry about 4 times, and
- from transport about 70 times.

Again both PM<sub>10</sub> and CO behave as gases, so a ratio analysis is valid.

On this basis, the peak 24-hour concentration of CO due to all sources is of the order of 1.5 mg m<sup>-3</sup>. This is similar to the levels found in many urban areas of NZ, and is largely due to transport emissions. This can be compared to the standards value of 8 mg m<sup>-3</sup>, for an 8-hour period for the standard. The 8-hour value in Rotorua is likely to be higher than the peak 24-hour value, but at the very worst by a factor of 3 (8/24), giving a worst case peak of 6 mg m<sup>-3</sup> compared to the standard of 8 mg m<sup>-3</sup>. Thus there will be no significant exceedences of CO at least on the grid scale level of 250m x 250m. It is possible there could be higher concentrations on very small scales right beside busy roads and intersections. This occurs throughout NZ and is a consequence of the high CO emissions from the national vehicle fleet.



## 9. Modelling Baseline Summary

This modelling study has been complex because of the scope of work attempted, and the very detailed nature of results obtained. The model has been run at a very fine scale (at 250m it is the finest resolution generally attempted anywhere for airshed models) and consequently needs a great deal of computer time to run. The individual modelling runs can take several days to process on even the fastest PC, and produce over 65Mb of output data.

Nevertheless, the results obtained are realistic and are consistent with the monitoring results from the three PM<sub>10</sub> monitoring sites in the city.

The patterns of PM<sub>10</sub> exposure across the city show high values in the west and southwest – where domestic heating emissions are high, as shown in the inventory.

Vehicle emissions do contribute to PM<sub>10</sub> levels, but much less so than the domestic emissions. There are likely to be some higher levels within 10-20m of busy roadways due to vehicle emissions, but these are only small localised areas and do not show up in the airshed modelling results.

Industrial emissions, with all the consent holders discharging PM<sub>10</sub> at their consent limits, do not result in particularly high concentrations.

Concentrations of other contaminants, particularly NO<sub>2</sub>, SO<sub>2</sub> and CO (or ozone) are not expected to be close to any standards or guidelines.

The test case of the model re-run using the 2006 dataset shows that there is substantial consistency in the meteorological data between 2001 and 2006, although some subtle differences show up in the airshed modelling. The ambient concentration patterns across the city change slightly, due to slight variations in the weather from year-to-year. The 2001 dataset gives slightly higher results – by a few percent – and this is the dataset used in all the modelling.

## 10. Reduction Strategies Analysis

Modelling next needs to be undertaken to analyse specifically the effects of possible emissions reduction strategies. The modelling results indicate that large areas of the city can experience exceedences of the PM<sub>10</sub> standard. The extent of reductions required is of the order of 50-60% for much of the residential area.

The following seven scenarios have been investigated:-

Scenario	Description
1 (BAU)	Domestic– +4% (based on census 2001 and 2006 provisional data) Transport– -15% Industry– no reduction Rubbish– -100% School – no change
2	Domestic– -40% across the LAMA Transport– -15% Industry– no reduction Rubbish– -100% School – -100%
3	Domestic– -60% across the LAMA Transport– -15% Industry– no reduction Rubbish– -100% School – -100%
4	Domestic– -40% Western suburbs only (complete grids to west of SH5) Transport– -15% Industry– no reduction Rubbish– -100% School – -100%
5	Domestic– -60% Western suburbs only (complete grids to west of SH5) Transport– -15% Industry– - no reduction Rubbish– -100% School – -100%
6	Domestic– -40% Six western suburbs only (complete grids for Western Heights, Pukehangi North, Pukehangi South, Mangakakahi, Fordland and Sunnybrook census area units) Transport– -15% Industry– - no reduction Rubbish– -100% School – -100%
7	Domestic– -60% Six western suburbs only (complete grids for Western Heights, Pukehangi North, Pukehangi South, Mangakakahi, Fordland and Sunnybrook census area units) Transport– -15% Industry– - no reduction Rubbish– -100% School – -100%

Figure 10.1 shows the for census area units used to determine the selected areas.



## Baseline

Firstly the current baseline map is repeated (from Figure 7.5 earlier).



This shows the peak 24-hour PM<sub>10</sub> concentrations across the city, based on the 2005 emissions inventory (and using the 2001 meteorology), with peaks up to 100 µg m<sup>-3</sup>, and large areas exceeding the standard of 50 µg m<sup>-3</sup>.

This is consistent with the monitoring results available.

## Scenario 1

Business as usual, but with a 15% reduction in transport emissions and a 4% increase in domestic heating emissions due to population growth.



This shows the anticipated pattern of peak 24-hour PM<sub>10</sub> concentrations across the city under a 'business as usual' scenario, with peaks still up to and exceeding 100 µg m<sup>-3</sup>, and large areas still exceeding the standard of 50 µg m<sup>-3</sup>.

This shows slightly wider areas of PM<sub>10</sub> exceedence compared to the baseline, mainly due to the 4% increase in domestic heating emissions assumed. The reductions in transport emissions have little effect, since these are generally not high in the areas where domestic emissions are high.



## Scenario 2

A 15% reduction in transport emissions and a 40% reduction in domestic heating emissions across the city.



This shows the anticipated future pattern of peak 24-hour PM<sub>10</sub> concentrations across the city under a 40% reduction scenario for domestic emissions, with peaks reduced to around 63 µg m<sup>-3</sup>, and some areas still exceeding the standard of 50 µg m<sup>-3</sup>.

Exceedences of the standard still occur, but they are much reduced over the current or baseline case.



### Scenario 3

A 15% reduction in transport emissions and a 60% reduction in domestic heating emissions across the city.



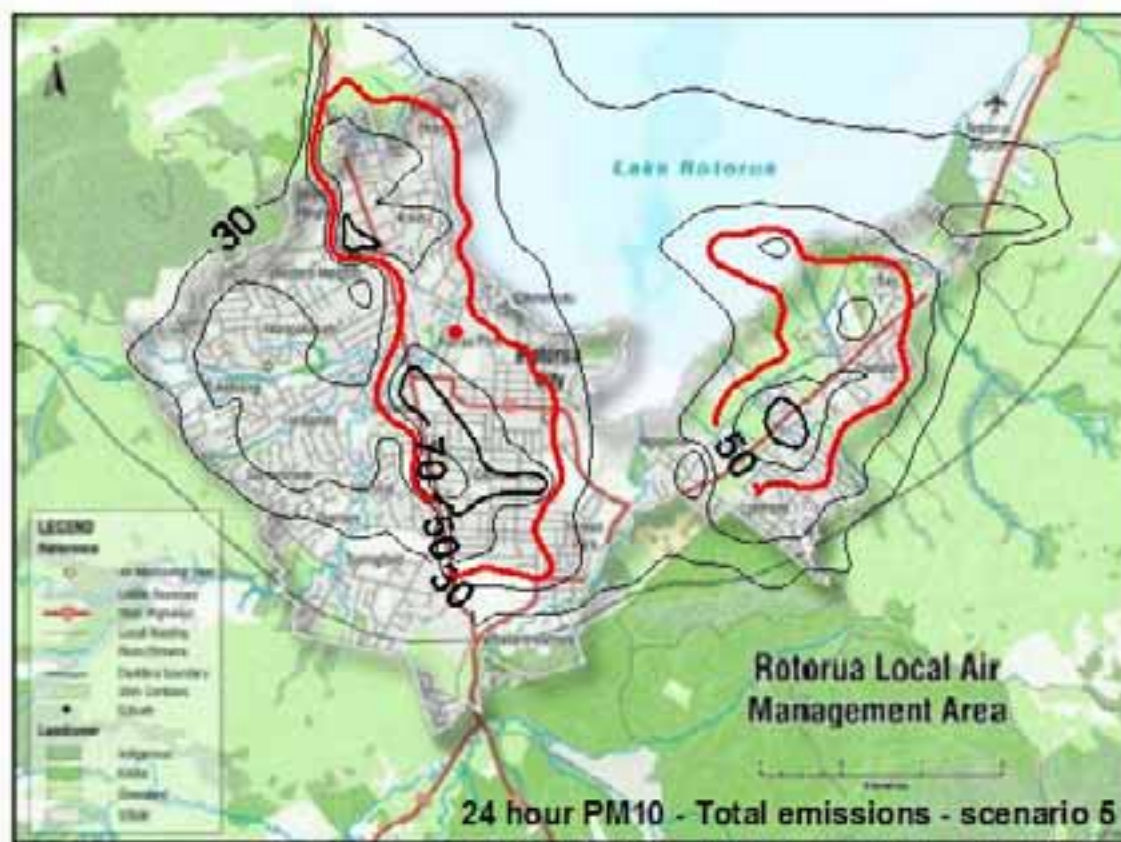
This shows the anticipated future pattern of peak 24-hour PM<sub>10</sub> concentrations across the city under a stronger 60% reduction scenario in domestic heating emissions, with peaks reduced to around 45 µg m<sup>-3</sup>, and the entire city being in compliance with the standard of 50 µg m<sup>-3</sup>.

Under this scenario there are no PM<sub>10</sub> exceedences anywhere in Rotorua.



## Scenario 5

A 15% reduction in transport emissions and a 60% reduction in domestic heating emissions from the western suburbs only (west of SH1).



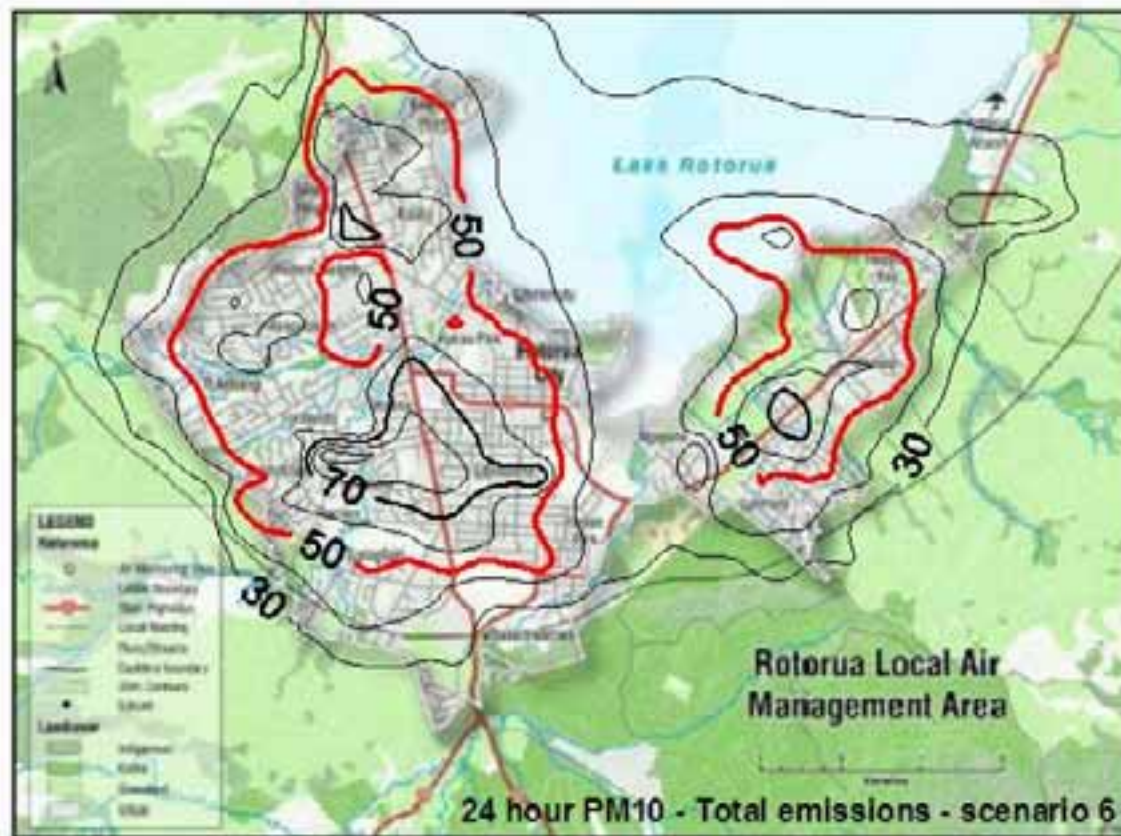
This shows the anticipated future pattern of peak 24-hour PM<sub>10</sub> concentrations across the city under partial 60% reduction scenario in domestic heating emissions just occurring west of State Highway 5.

Here more significant concentration reductions can be seen in the areas where the emissions reduction occurs, to the extent that exceedences are eliminated in this area. However there is still little effect in areas to the east of SH5, where peaks still remain above 80 µg m<sup>-3</sup>.



## Scenario 6

A 15% reduction in transport emissions and a 40% reduction in domestic heating emissions from the Western Heights, Pukehangi North, Pukehangi South, Mangakakahi, Fordland and Sunnybrook census area units. (These are the 6 northern-most of the larger CAU areas shown in Figure 10.1, and represent about half of the area west of SH5 considered in scenarios 4 and 5).

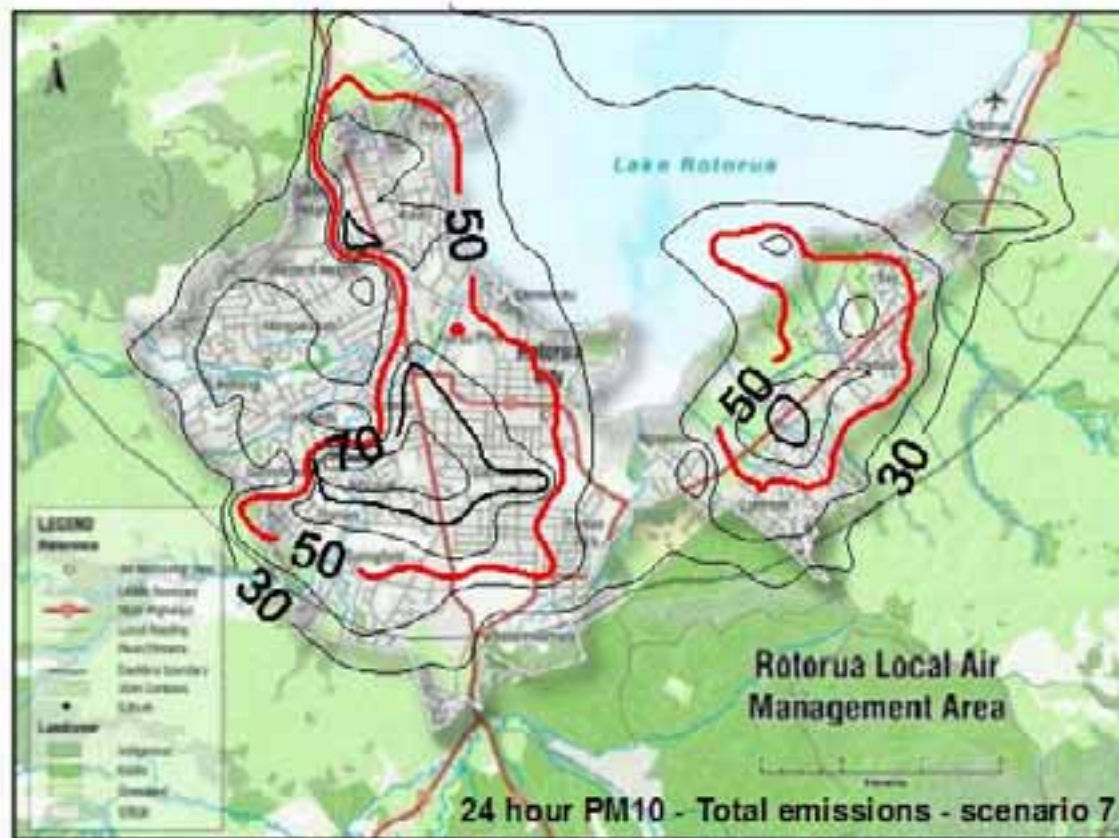


This shows the anticipated future pattern of peak 24-hour PM<sub>10</sub> concentrations across the city under partial 40% reduction scenario in domestic heating emissions just in 6 CAU areas in the northern part west of State Highway 5.

Here some concentration reductions can be seen in the areas where the emissions reduction occurs. However there is still little effect in other areas, where peaks still remain above 90 µg m<sup>-3</sup>.

## Scenario 7

A 15% reduction in transport emissions and a 60% reduction in domestic heating emissions from the Western Heights, Pukehangi North, Pukehangi South, Mangakakahi, Fordland and Sunnybrook census area units.



This shows the anticipated future pattern of peak 24-hour PM<sub>10</sub> concentrations across the city under partial 60% reduction scenario in domestic heating emissions just in 6 CAU areas in the northern part west of State Highway 5.

Here more significant concentration reductions can be seen in the areas where the emissions reduction occurs, to the extent that exceedences are eliminated. However there is still little effect in other areas, where peaks still remain above 90  $\mu\text{g m}^{-3}$ .

## Discussion of reduction scenarios

These results show the nature of the effects that can be expected in the peak 24-hour PM<sub>10</sub> concentrations around Rotorua under various emissions reductions scenarios.

The only scenario that completely eliminates exceedences is one that achieves a 60% reduction in domestic emissions across the whole city. Reductions of 40% achieve some substantial benefits, but do not eliminate exceedences completely.

Scenarios that achieve 60% reduction in certain areas, generally result in eliminating exceedences in those areas, but have little or no effect on other areas, even quite close.

This appears to be an indication of the meteorological factors prevailing when concentrations get high. As shown in the meteorological analysis, these are night-time occurrences calms or very light winds with low level inversions. Under these conditions the emissions do not move very much, even under the light drainage flows down the valleys. The exception appears to be in the eastern part of the city, where the modelling shows high concentrations can occur out over the lake, obviously from drainage flows off the eastern hills carrying emissions for a few hundred metres to the west. This situation does not occur to the same extent in the shallower western hills, where emissions (and any reductions in these) tend to stay within 100-200m of the source.



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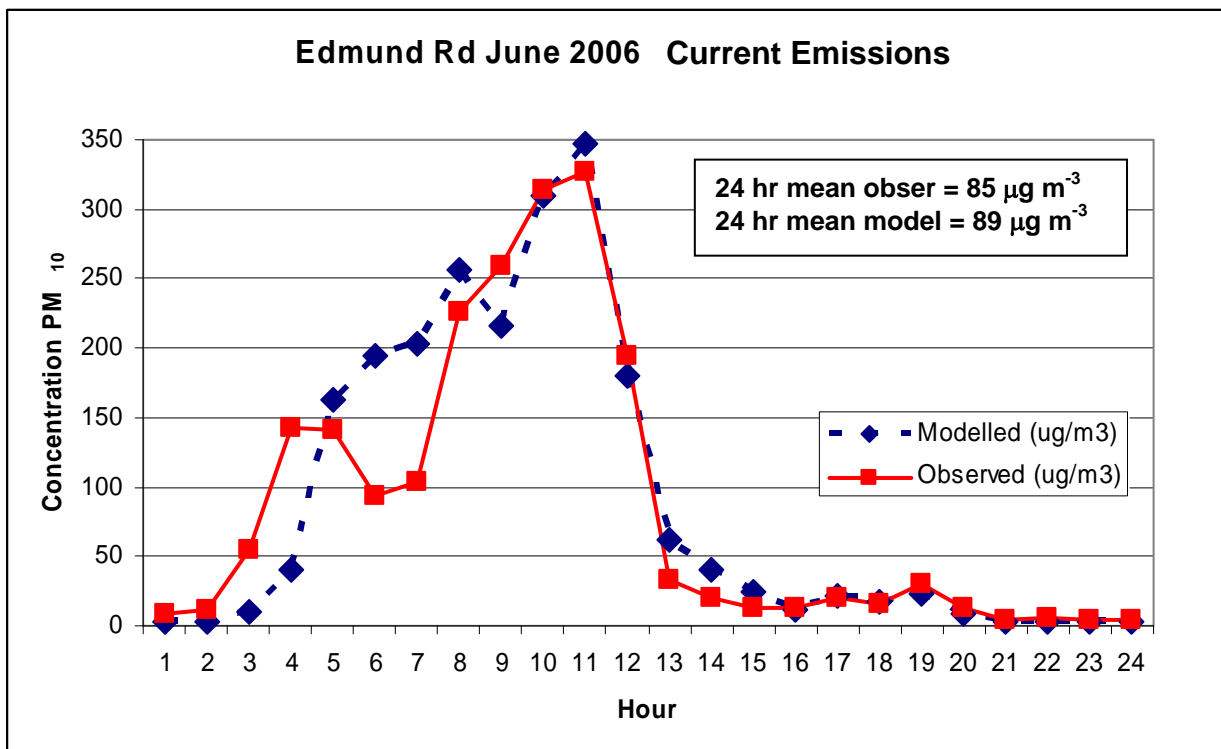
## Acknowledgements

This work could not have been completed without the input, encouragement, reviews and advice from Shane Iremonger (Environment Bay of Plenty), and Dr Bruce Graham (Graham Environmental Consulting Ltd.)

## Appendix A - Box Model

### Box model

The box modelling results give a primary check on the main modelling results for PM<sub>10</sub>. This model can only be used to examine a particular worst case. Figure A.1 shows the results for a model run for the night of 9 June 2006, compared with the Edmund St monitoring record for that night.



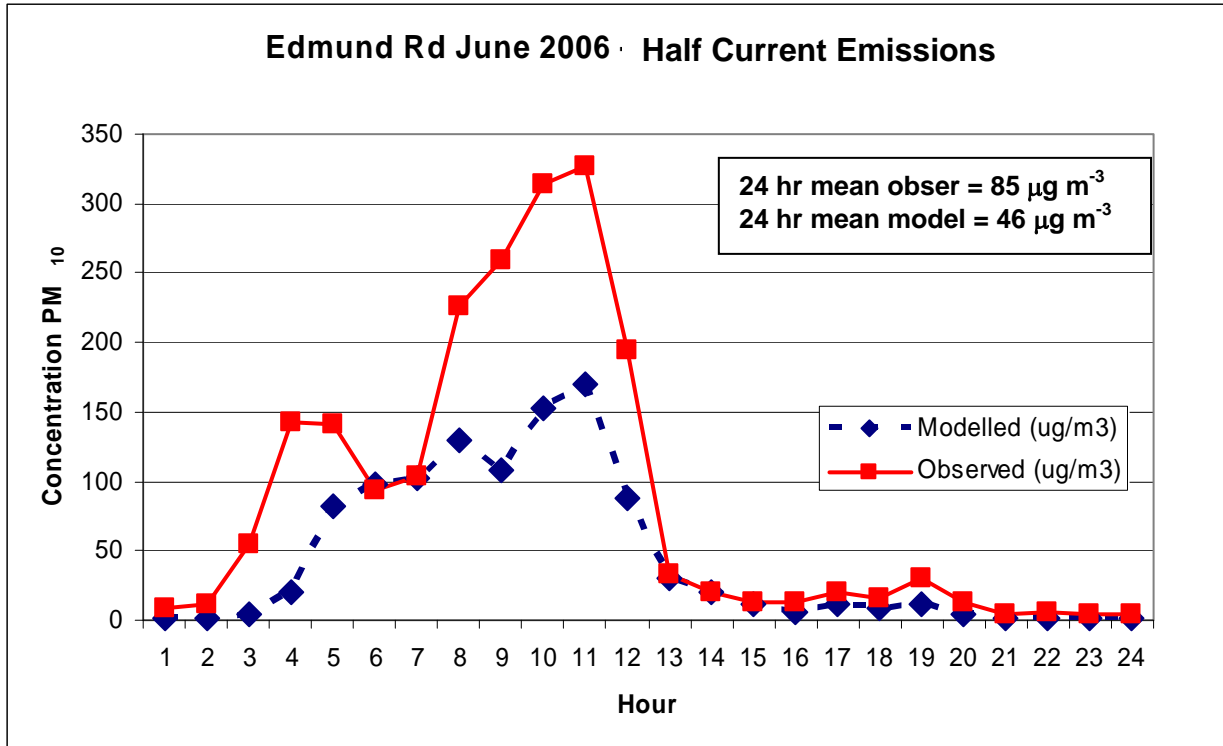
**Figure A.1** Box model results and monitoring record for 9 June 2006, Edmund Rd. Current full domestic heating emissions.

Figure A.1 shows a remarkably good level of agreement, not only with the profile through the night, but also on the peaks and 24-hour average.

The agreement cannot be made any better without having a detailed knowledge of (a) the actual hour-by-hour emissions on that particular night, and (b) the detailed meteorology of that night. Neither of these pieces of information are available, but nevertheless, the agreement is excellent considering this lack of detail. This is due to the fact that this is a carefully selected, cold calm night that is close to the worst case for both the emissions and the meteorology. This level of model agreement would almost certainly not occur on a more generic night.

The box model approach is useful for examining the effect of mitigation strategies. For instance if it was somehow possible to obtain an overall 50% reduction in emissions in this area – say by replacing half of the wood heaters, or by upgrading burners to produce half as much wood smoke – then the expectations in terms of air quality can be modelled.

Figure A.2 shows the result of a 50% reduction. Whilst there are still high hourly values in the middle of the night, the all important 24-hour average concentration decreases from  $89 \mu\text{g m}^{-3}$  to  $46 \mu\text{g m}^{-3}$ . This area would then be in compliance with the standard.



**Figure A.2** Box model results and monitoring record for 9 June 2006, Edmund Rd. Case with the domestic heating emissions all reduced by 50%

Whilst it would be possible to construct a box model for each grid area in the city, these would not show all of the relevant features, and may miss some important effects – such as transport of pollution in drainage flows. It is also difficult to incorporate vehicle and industrial emissions in the same box model as domestic heating, since they all behave differently in the atmosphere. This modelling has worked well in this case, because the grid area selected is not very influenced by vehicle or industrial sources.

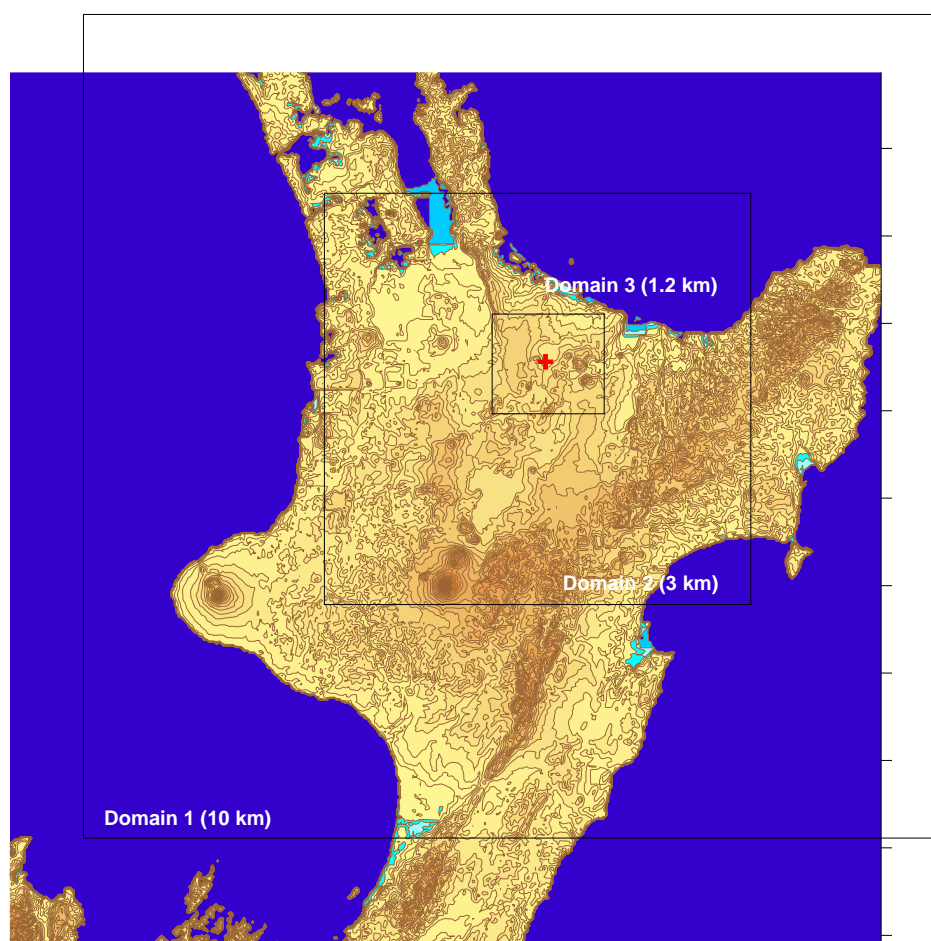
## Appendix B - Meteorological Model

### Model methodology detail

This study used the capabilities of two models, TAPM and CALMET in order to develop realistic winds over the Rotorua region. The prognostic numerical model, TAPM (CSIRO's "The Air Pollution Model") was used to develop upper air profiles which were then used as input into the CALMET diagnostic meteorological model.

Figure B.1, shows the three nested TAPM model domains employed over the Rotorua region.

TAPM Modeling domains used for Rotorua Meteorological Modeling



**Figure B.1** Nested meteorological grids centred over Rotorua.

The TAPM model was setup using 25 vertical levels. The outermost nest covered 600km x 600km at a resolution of 10 km, the second nest also covered 60 x 60 grid cells but at a resolution of 3 km and, the innermost nest centred directly over Rotorua had a resolution of just 1.2 km. The model was run using standard defaults.

The CALMET meteorological model used an extended north-south meteorological domain which had 158 grid cells in the x-direction and 203 grid cells in the y-direction. A grid resolution of 1km was chosen. The reason the model domain used an extended north-south

domain was to incorporate the high terrain of the central north island. The dominant wind flow is from the southwest, i.e., directly from the high terrain to the south and southwest. Model test runs were done assuming a fine scale meteorological grid centred over Rotorua using a horizontal resolution of 250m and covering an area of just 63km x 55km. Wind fields at this finer resolution were then compared to winds on the larger coarser domain at 1km to see which domain and grid resolution performed best. It was concluded that the winds were more realistically represented using the 1km CALMET domain where the dominant terrain was being incorporated as this more accurately portrayed the dominant flows over Rotorua and the diurnal flow patterns where drainage flow and calm conditions seem to prevail at night.

Figure B.2, shows the CALMET meteorological domain, the Landuse categories, terrain contours and surface and upper air stations as used in the CALMET modelling (shown in Table B.1). The hourly upper air profiles were derived from TAPM.

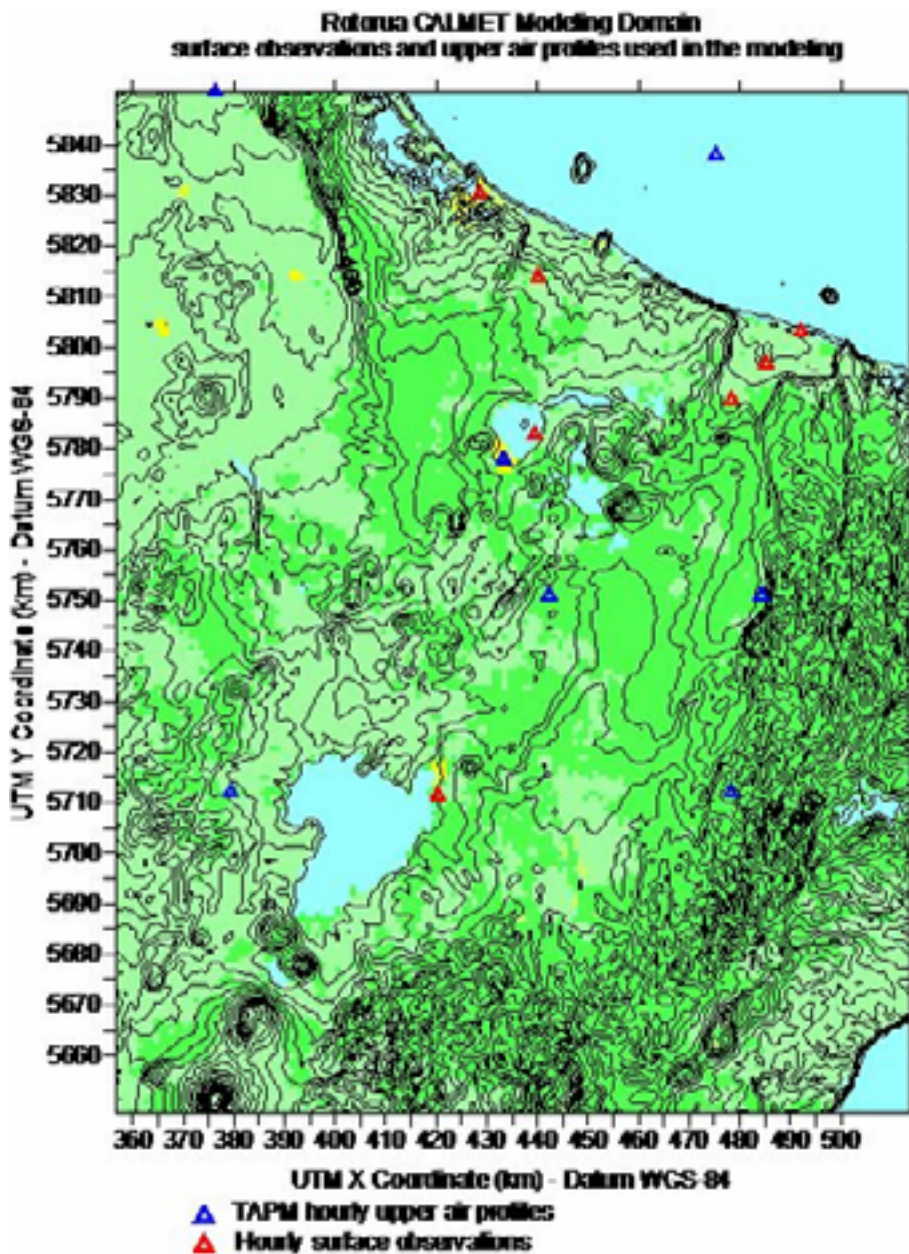


Figure B.2 Landuse categories and meteorological stations used.

**Table B.1 Automatic weather stations used in Calmet model**

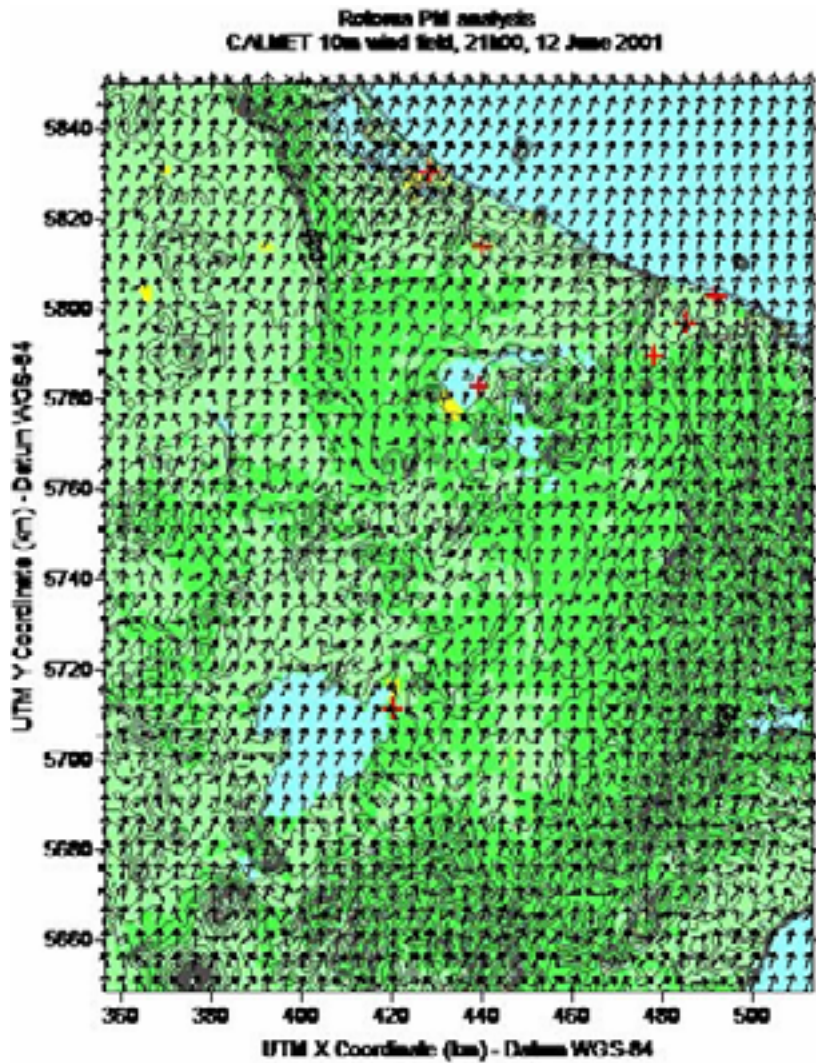
No	Site Number	Site Name	Easting (m)	Northing (m)	Height (m)
1	1547	Paeroa Aws	2748000	6422100	18
2	1551	Waihi, Barry Road Ews	2762300	6419800	114
3	1610	Tauranga Harbour	2791016	6390832	3
4	1614	Tauranga Aerodrome	2791005	6388056	4
5	1615	Tauranga Aero Aws	2792100	6387400	4
6	23908	Toenepi Ews	2738300	6383800	48
7	12616	Ruakura Ews	2714000	6377900	40
8	12428	Te Puke Ews	2802600	6370600	91
9	2112	Hamilton Aws	2715700	6368400	53
10	2110	Hamilton Aero	2715466	6368198	50
11	1672	Whakatane Aero	2854600	6356800	6
12	1673	Whakatane Aero Aws	2854600	6356800	7
13	21866	Kawerau Ews	2838800	6344700	18
14	1770	Rotorua Aero Aws	2800900	6338800	283
15	1768	Rotorua Aero 2	2800966	6337718	287
16	1858	Taupo Aws	2777900	6268900	400
17	1856	Taupo Aero	2778029	6268243	400
18	9001	Edgecumbe	2846542	6350942	27
19	9002	Rotorua (Peririka)	2794248	6335478	310
20	9003	Tokoroa	2760400	6327400	330

The yellow regions of the Landuse map show the urban areas. The city of Taupo and Rotorua can be clearly seen. Various shades of green demarcate forested vs. agricultural land. The terrain contours show the elevated terrain of the central North Island to the southeast and south. Mt Ruapehu and Ngarauhoe southwest of Lake Taupo are also clearly visible. Hourly TAPM upper air profiles were used as direct inputs into the CALMET model. It was deemed more realistic to use several strategically placed, hourly, upper air profiles from TAPM as input into CALMET than to use actual profile data which is only recorded at three sites around the country, Whenuapai in the north, Paraparaumu near Wellington and Invercargill in the far south of the South Island. Recordings from these three sites occur twice a day, approximately midday and midnight as opposed to the prognostic model's hourly data. Further these sonde stations are located in completely different synoptic regimes to that over Rotorua which means they are not valid for the Rotorua region at all. A further issue with the sonde data is the time of day that the data is recorded, i.e., midday and midnight. Ideally the data should be collected just before sunrise and just after sunset. The reason for this is that the growth of the mixing height depends on the pre-sunrise temperature profile.

Surface observations from several sites around the Rotorua region were used directly into the CALMET model. One weighting value was supplied to represent all surface stations – given in km as a maximum radius of influence. In this analysis a value of 10 km was deemed sufficient for all surface stations. Terrain was given a maximum radius of influence of 15 km.

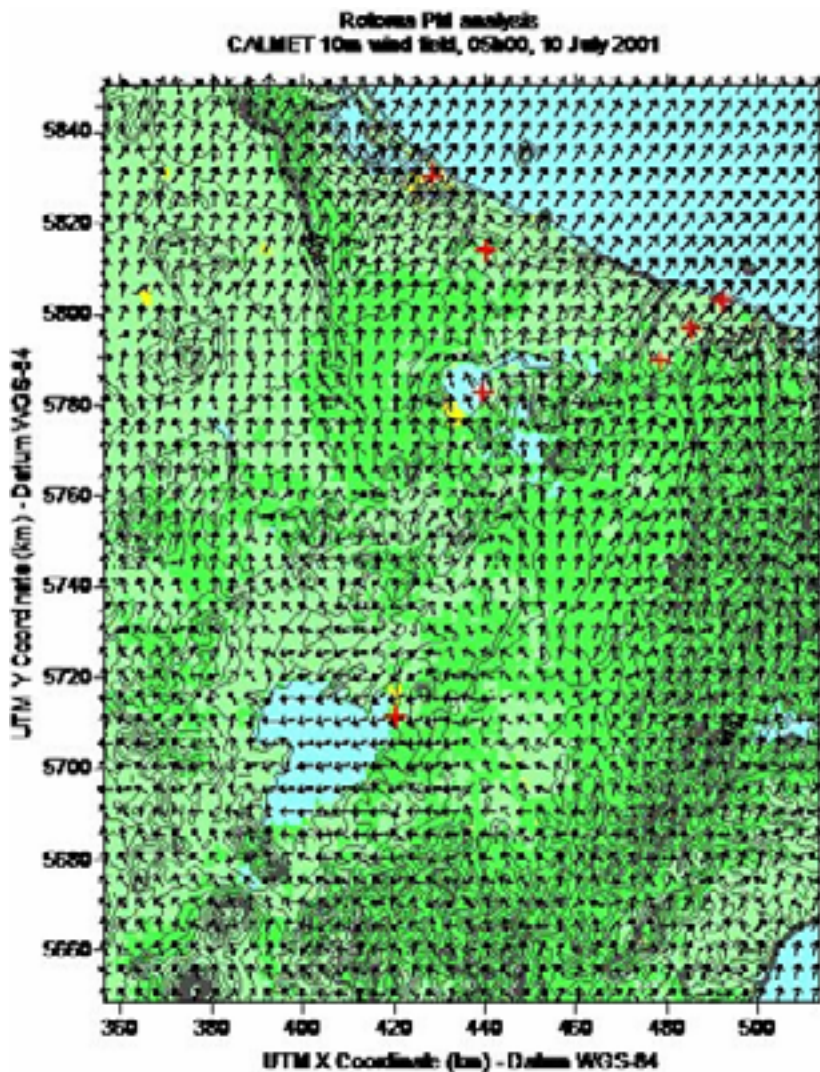
Figure B.3, shows a stable, nighttime wind field over the model domain. This plot reflects the dominant windflow from the southwest. Light nocturnal drainage flow toward Rotorua lake is common.





**Figure B.3** Stable nighttime wind example.

Figure B.4 reflects neutral stability conditions. The wind is from the west at night. The flow over Rotorua has a much more westward orientation to it than in the plot before and the winds are stronger.



**Figure B.4 Neutral stability winds example.**

A comparison of TAPM model data at Rotorua compared with actual surface data at Rotorua is shown in this series of wind roses below. A simple discussion for each event follows;

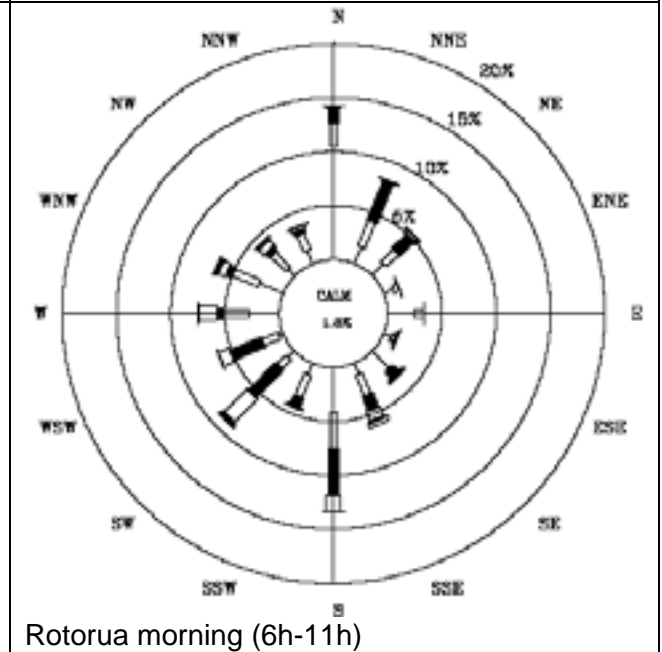
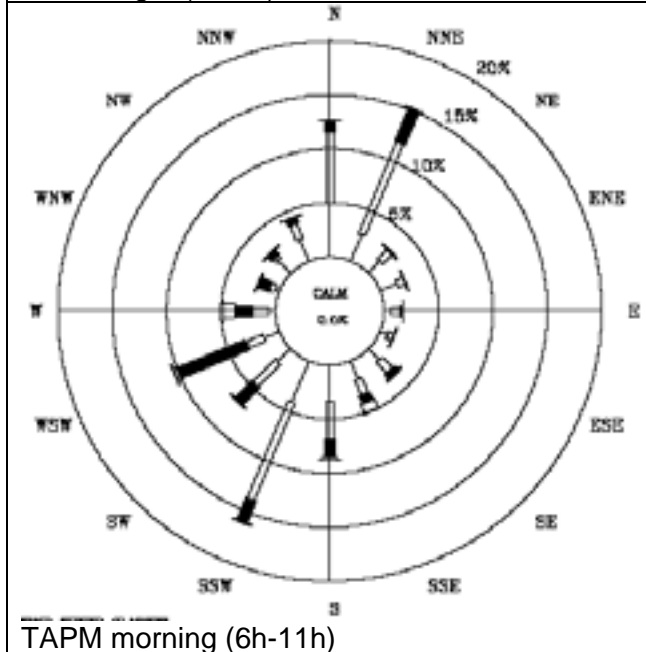
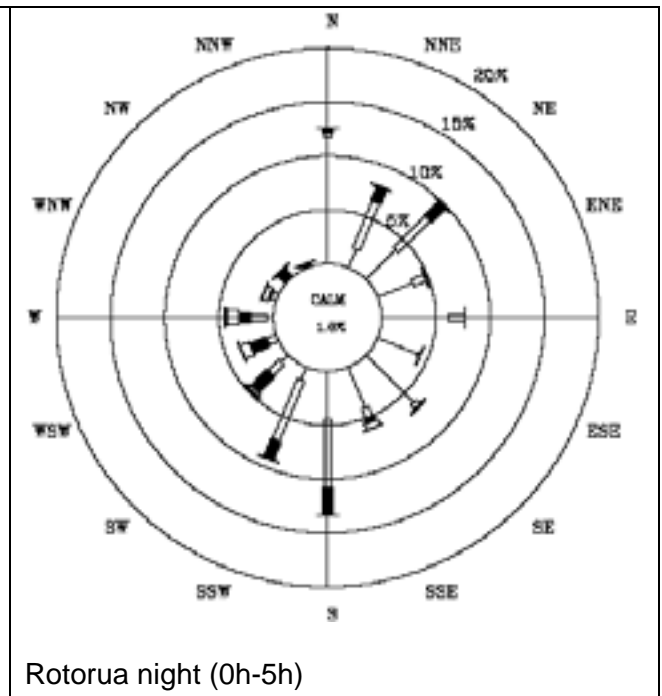
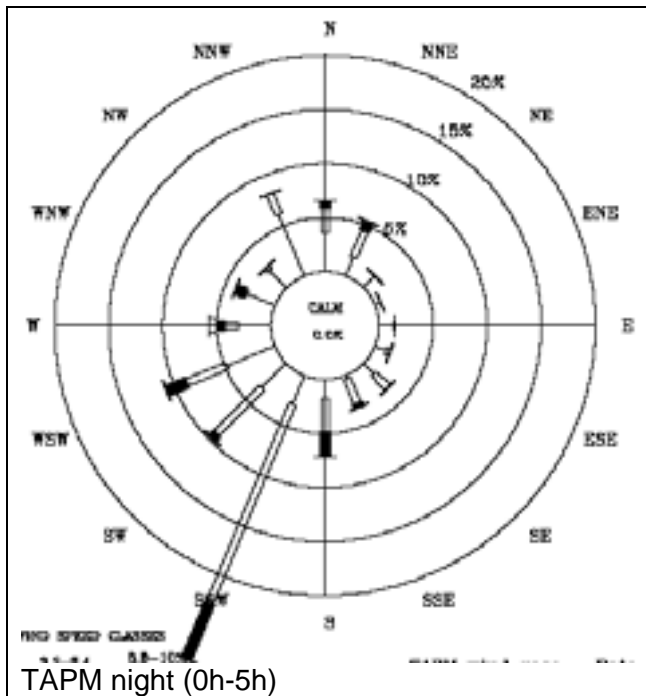
Nighttime (00h00 – 05h00) – TAPM predicts predominantly SSW drainage flows compared to what actually happens at Rotorua where the dominant flow has more of a southerly orientation.

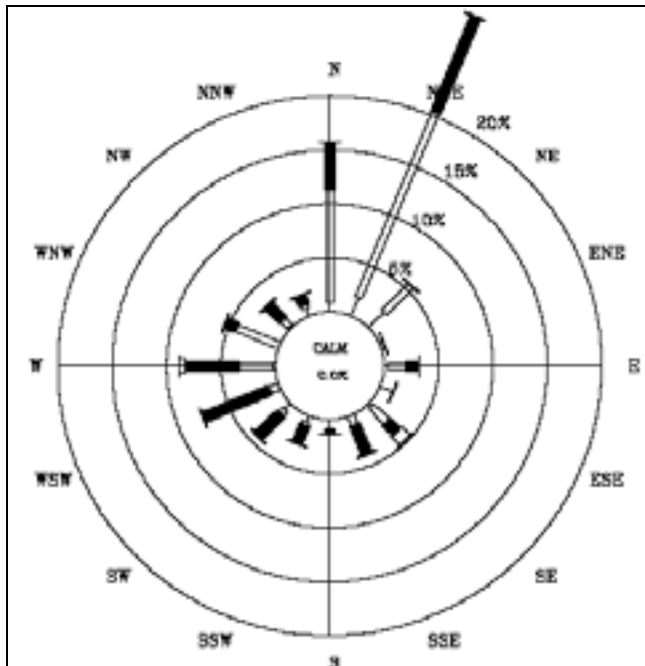
Morning (06h00 – 11h00) – actual data at Rotorua shows strong north south alignment of flow. TAPM does not do too badly correctly picking up on the north south flow but with the alignment skewed NNE – SSW rather than north-south. Flow from all other directions is nominal, all under 5% or between 5% and 10%. The model reflects well with actual data.

Afternoon (12h00 – 17h00) – Again, TAPM does not do badly when compared to actual data at Rotorua. The afternoon modelled roses show the dominance of the afternoon sea breeze from the NE. The second most dominant flow is from the west which probably reflects the overriding westerly synoptic conditions when the sea breeze does not occur. The model does quite well here when compared to the actual data.

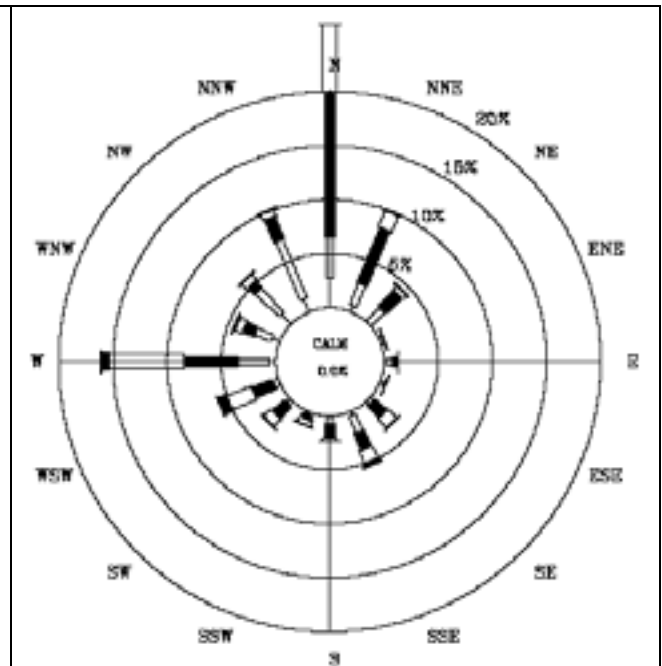
Evening (18h00 – 23h00) - the evening wind roses reflect the dying off of the sea breeze from the north and a growth of the west and southwest flow.

In summary, the TAPM modelled winds do a good job when compared with the actual data at Rotorua. It is important to remember here that TAPM only 'sees' terrain at a 1km resolution whereas the actual wind data at Rotorua reflects the immediate terrain around it.

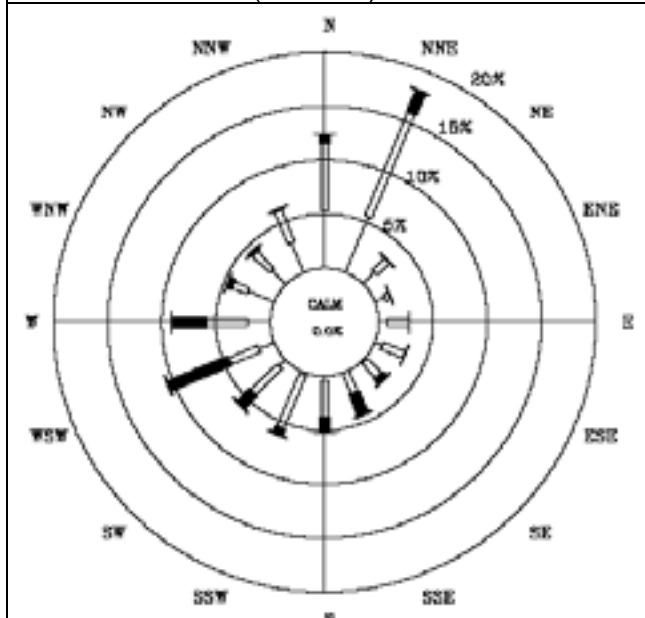




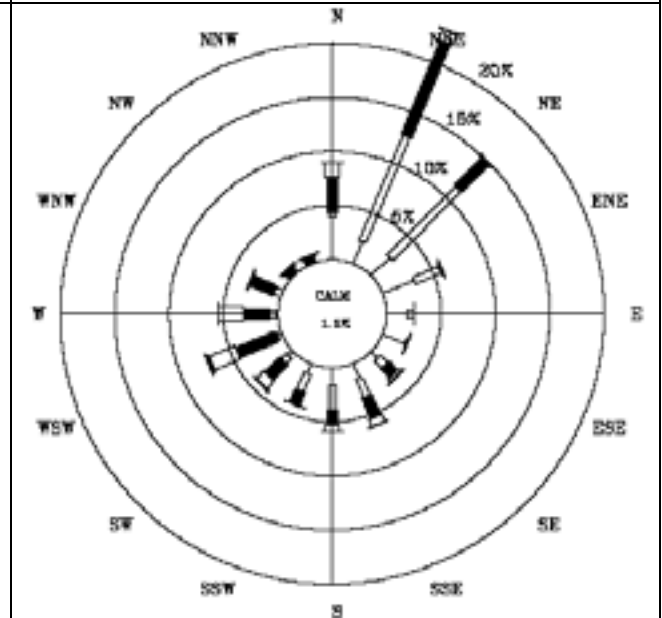
TAPM afternoon (12h-17h)



Rotorua afternoon (12h-17h)



TAPM evening (18h-23h)



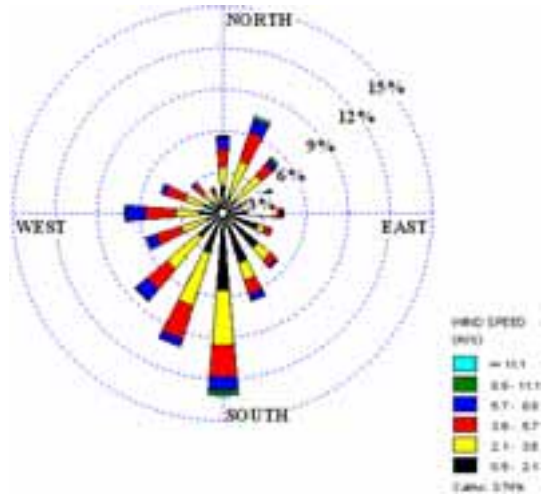
Rotorua evening (18h-23h)

Note that these comparisons are only with the TAPM meteorological data, which is used as input to the Calmet meteorological model. The actual meteorological data used in the modelling has not been extracted from Calmet, but is likely to show a much better agreement.

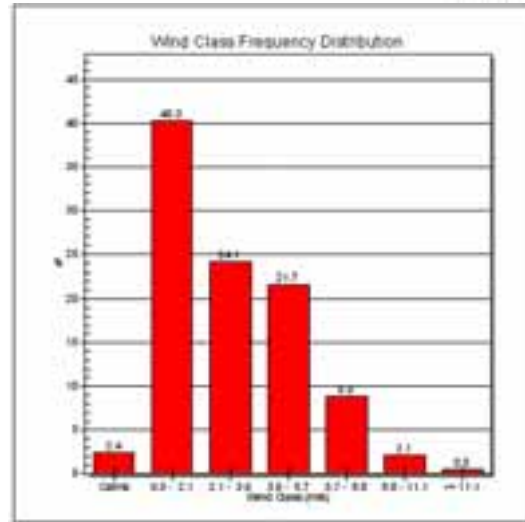
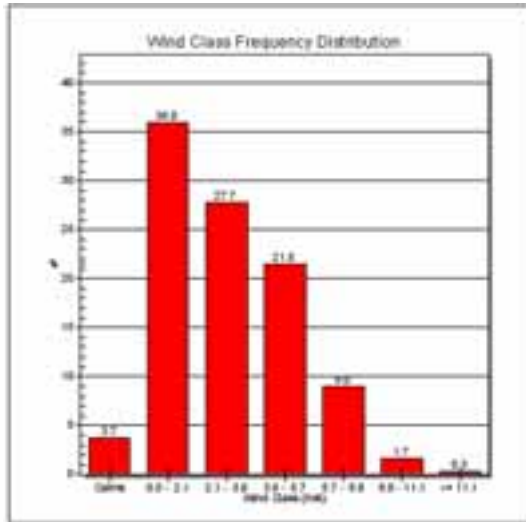
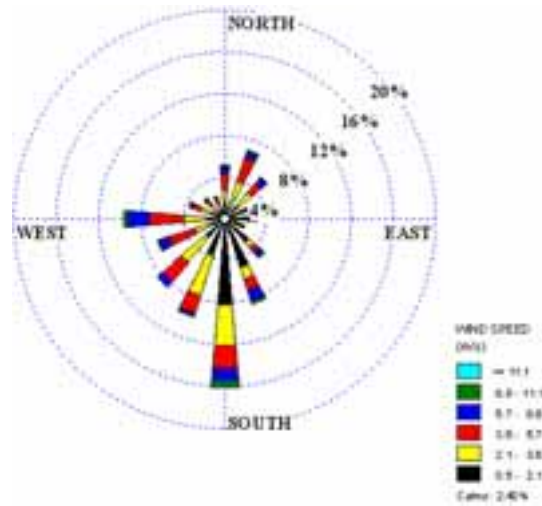


**Appendix C - Comparison Between 2001 & 2006 Meteorology**

**Rotorua: 1<sup>st</sup> May to 30<sup>th</sup> September 2001 (all hours)**



**Rotorua: 1<sup>st</sup> May to 30<sup>th</sup> September 2006 (all hours)**

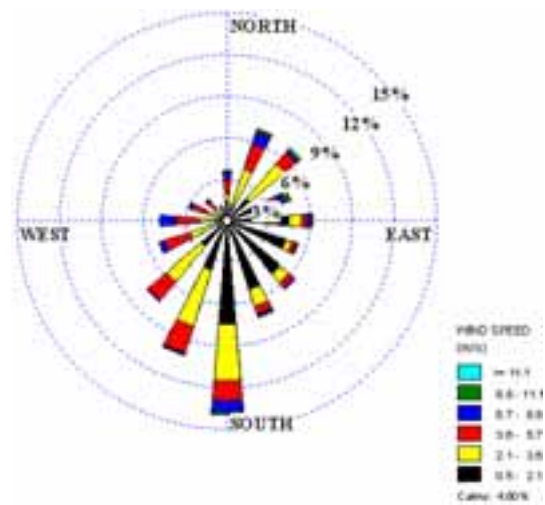


<b>Wind speed – ALL HOURS May to September 2001</b>	
Mean	2.937415
Standard Error	0.035487
Median	2.6
Mode	1
Standard Deviation	2.148968
Sample Variance	4.618065
Kurtosis	0.974503
Skewness	0.987228
Range	13.9
Minimum	0
Maximum	13.9
Sum	10771.5
Count	3667

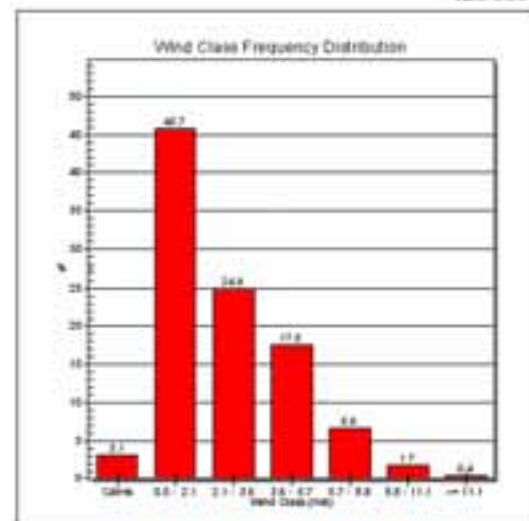
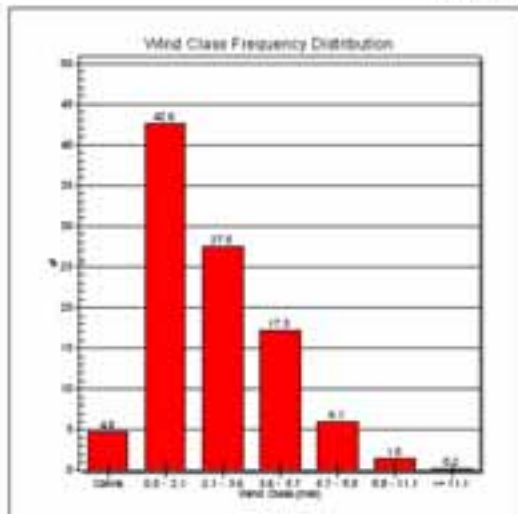
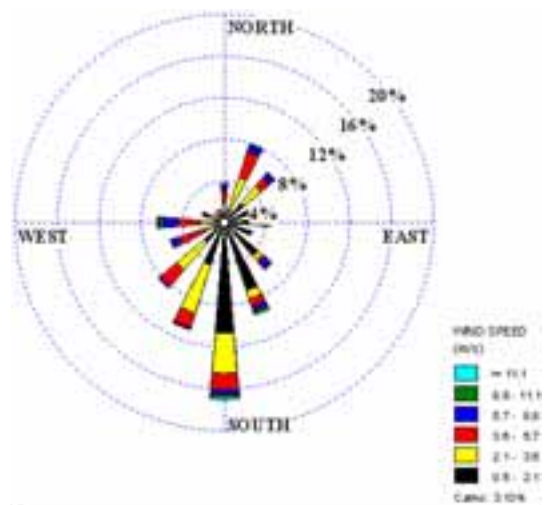
<b>Wind speed – ALL HOURS May to September 2006</b>	
Mean	3.178392
Standard Error	0.037391
Median	2.583333
Mode	1.027778
Standard Deviation	2.265781
Sample Variance	5.133762
Kurtosis	2.193857
Skewness	1.185513
Range	18.02778
Minimum	0
Maximum	18.02778
Sum	11671.06
Count	3672



**Rotorua: 1<sup>st</sup> May to 30<sup>th</sup> September 2001 (6pm to 6am)**



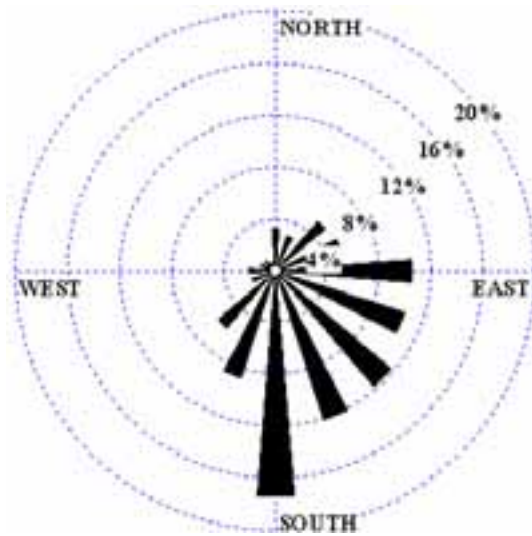
**Rotorua: 1<sup>st</sup> May to 30<sup>th</sup> September 2006 (6pm to 6am)**



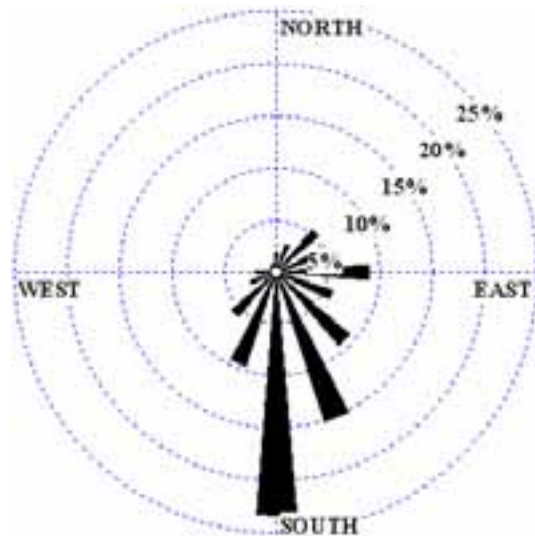
<b>Wind speed: 6pm – 6am May to September 2001</b>	
Mean	2.542381
Standard Error	0.045042
Median	2.1
Mode	1
Standard Deviation	2.005251
Sample Variance	4.02103
Kurtosis	1.78024
Skewness	1.242775
Range	12.4
Minimum	0
Maximum	12.4
Sum	5039
Count	1982

<b>Wind speed: 6pm – 6am May to September 2006</b>	
Mean	2.853449
Standard Error	0.048
Median	2.583333
Mode	1.027778
Standard Deviation	2.137498
Sample Variance	4.568898
Kurtosis	2.626122
Skewness	1.365461
Range	14.91667
Minimum	0
Maximum	14.91667
Sum	5658.389
Count	1983

**Rotorua: 1<sup>st</sup> May to 30<sup>th</sup> September  
2001 (6pm to 6am)  
0.5 – 2.1 ms<sup>-1</sup> wind speed only**



**Rotorua: 1<sup>st</sup> May to 30<sup>th</sup> September  
2006 (6pm to 6am)  
0.5 – 2.1 ms<sup>-1</sup> wind speed only**



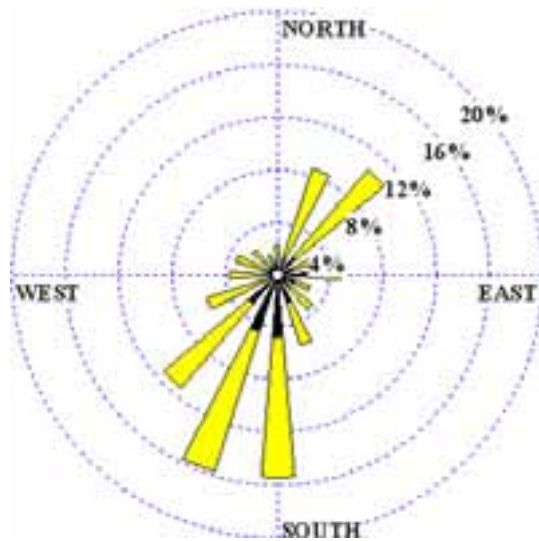
**Wind speed: 6pm – 6am  
May to September 2001  
0.5 – 2.1 m/s only**

Mean	1.181598
Standard Error	0.017614
Median	1
Mode	1
Standard Deviation	0.55392
Sample Variance	0.306827
Kurtosis	-0.99784
Skewness	0.387651
Range	1.6
Minimum	0.5
Maximum	2.1
Sum	1168.6
Count	989

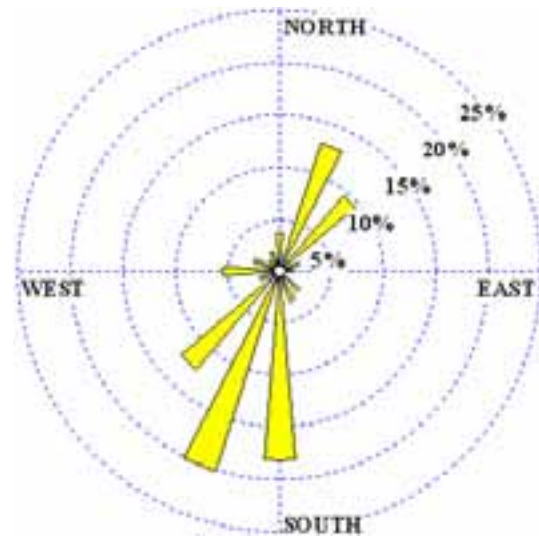
**Wind speed: 6pm – 6am May  
to September 2006  
0.5 – 2.1 m/s only**

Mean	1.297685
Standard Error	0.017698
Median	1.027778
Mode	1.027778
Standard Deviation	0.532993
Sample Variance	0.284082
Kurtosis	-1.20482
Skewness	0.031922
Range	1.527778
Minimum	0.527778
Maximum	2.055556
Sum	1177
Count	907

**Rotorua: 1<sup>st</sup> May to 30<sup>th</sup> September  
2001 (6pm to 6am)  
2.1 – 3.6 ms<sup>-1</sup> wind speed only**



**Rotorua: 1<sup>st</sup> May to 30<sup>th</sup>  
September 2006 (6pm to 6am)  
2.1 – 3.6 ms<sup>-1</sup> wind speed only**



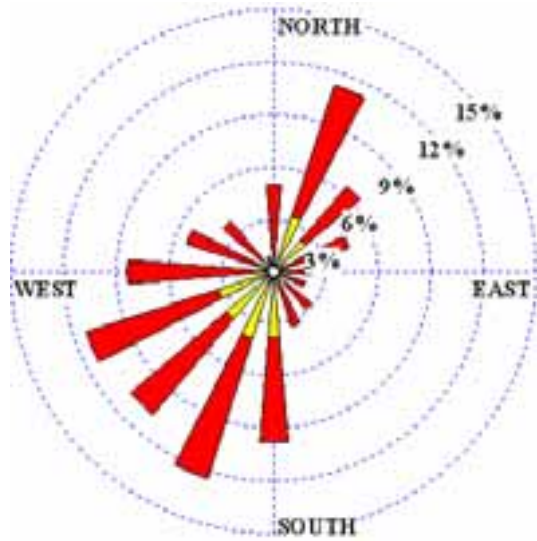
**Wind speed: 6pm – 6am May  
to September 2001  
2.1 – 3.6 m/s only**

Mean	2.781887
Standard Error	0.020914
Median	2.6
Mode	2.1
Standard Deviation	0.536069
Sample Variance	0.28737
Kurtosis	-1.24543
Skewness	0.129593
Range	1.5
Minimum	2.1
Maximum	3.6
Sum	1827.7
Count	657

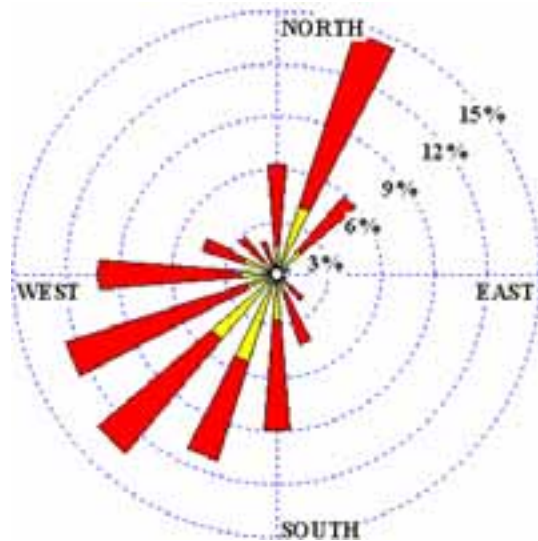
**Wind speed: 6pm – 6am May  
to September 2006  
2.1 – 3.6 m/s only**

Mean	2.810345
Standard Error	0.013364
Median	2.583333
Mode	2.583333
Standard Deviation	0.249299
Sample Variance	0.06215
Kurtosis	-1.97699
Skewness	0.185491
Range	0.5
Minimum	2.583333
Maximum	3.083333
Sum	978
Count	348

**Rotorua: 1<sup>st</sup> May to 30<sup>th</sup> September  
2001 (6pm to 6am)  
3.6 – 5.7ms<sup>-1</sup> wind speed only**



**Rotorua: 1<sup>st</sup> May to 30<sup>th</sup> September  
2006 (6pm to 6am)  
3.6 – 5.7 ms<sup>-1</sup> wind speed only**



***Wind speed: 6pm – 6am May  
to September 2001  
3.6 – 5.7 m/s only***

Mean	4.390692
Standard Error	0.034085
Median	4.1
Mode	3.6
Standard Deviation	0.697696
Sample Variance	0.486779
Kurtosis	-0.91337
Skewness	0.498078
Range	2.1
Minimum	3.6
Maximum	5.7
Sum	1839.7
Count	419

***Wind speed: 6pm – 6am May  
to September 2006  
3.6 – 5.7 m/s only***

Mean	4.377451
Standard Error	0.030343
Median	4.111111
Mode	3.611111
Standard Deviation	0.673731
Sample Variance	0.453913
Kurtosis	-1.02342
Skewness	0.430242
Range	2.055556
Minimum	3.611111
Maximum	5.666667
Sum	2158.083
Count	493